K. GLADKOV

THE POWERHOUSE OF THE ATOM

K. GLADKOV

THE POWERHOUSE OF THE ATOM

CONTENTS

Chapter I
ON THE EVE OF A GREAT DISCOVERY
A Dream of the Impossible 9
'Plum Pudding' 11
Becquerel's Mistake 14

Chapter II
RADIOACTIVITY
A Polish Girl's Discovery 17
The Radioactive Families 21
Almost 'Perpetual Motion' 25

Chapter III
ANOTHER RIDDLE OF NATURE
The Great Emptiness 27
How is the Atom Constructed? 29
What is Meant by 'Energy Level' and 'Electron-Volt'? 31
An Inquisitive Doctor 34
What is an Isotope? 35
An Atom-Sorting Machine 36
The World of Minute Particles and Enormous Energies 38
'Atomic Artillery' 38

Chapter IV
THE SCIENTISTS' TOOLS
How They Managed to Count Atoms 43
Fog That Makes the Invisible Visible 45
A Simpler Than Simple Instrument 47
'Cold Boiling' 48
A 'Lilliputian Thunderstorm' 50
Again That Photographic Plate 52
Larger Calibres 52
At New Cross Roads 57

Chapter V
THE KEY TO THE ATOMIC NUCLEUS
New Radiation 61
Enter the Neutron 63
The Clue to Nuclear Structure 65
The Cap of Fortunatus 67
Artificial Radioactivity 69
Another Mistake! 71
The Family of Uranium Isotopes 75
The Cherished Goal Reached 75

Chapter VI
ABOUT 'HORRIBLE THEORY'
Almost Back at the Beginning 79
Particle-Waves and Wave-Particles 80
Paradoxes of Wave Motion 81
How Electromagnetic Waves Are Formed 83
What is Light? 83
Photons, the Particles of Light 83
The Great Law 89
'What is Mass Defect'? 91
Nuclear Binding Energy 94
But What Is Radioactivity? 99
Briefly About Heat 104
The Thermonuclear Reaction 106

Chapter VII
CONTROLLED NUCLEAR FISSION
Obtaining the First Artificial Elements 111
'Atomic Matches' 113
A Controlled Chain Reaction 114
Atoms and a Game of Billiards 115
Water That Is Heavier Than Water 117

Critical Mass 118
When It's Not a Vice To Be Late 120
A 'Mirror' for Neutrons 122
A 'Bonfire' in a Laboratory 123
The Atomic Bomb 124
Once More About Neutrons 125
The Road to 'Transurania' 128

Chapter VIII

NUCLEAR REACTORS

What is a Reactor? 133
In Pencils and in Reactors 134
A Heavy-Water Reactor 136
A Homogeneous Reactor 138
Atomic 'Flames' Under Water 139

Chapter IX

A BRAND-NEW INDUSTRY

Fertile Materials 143
How Uranium and Thorium are Refined 143
Factories for Nuclear Fuel 147
Nuclear Fuel from Man's 'Second Nature' 149
Thorium-232 151
Stellar Fuel' 152

Chapter X

THE MARCH OF ATOMIC POWER

How Much Longer Will People Burn Money? 157
Steam Boiler vs Nuclear Reactor 158
The First One in the World 160
New Ideas 164
When One Log Becomes Two 169
The Dream Begat a Plan, the Plan a Dream 172
'SP' 174
'Teaser' 175
'Arbus' 177
Self-Propelled Atomic Generator 178
'Romashka' 179
Atoms to Irrigate Deserts 181

Chapter XI

THE 'YOUNGER' BROTHER OF ATOMIC ENERGY

What Does a Capful of Smoke Cost? 185
Precious Waste 187
'Labelled' Atoms 192
Isotopes in Biology 195
Isotopes in Medicine 197
Radiation Hazards 200
A Clock That Measures Millenia 202
'Hot Labs' and 'Iron Hands' 204

Chapter XII

THE FUTURE OF ATOMIC POWER

Blazing a New Trail 209
On Engines in General 209
The First Atomic Ice-Breaker—The 'Lenin' 212
Atomic Locomotives 215
Atomic Aircraft 216
Interplanetary Spaceships of the Future 219
Ion Engine 221
Photon Rockets 222
A Nuclear Battery 225

Chapter XIII

WHAT ARE NUCLEAR FORCES?

A Strange Game 229
What Attracts Electrons to Protons 230
Enter a New Particle, the Meson 232
The Meson Family 233
Superheavy Particles or Hyperons 235
What Can There Be in Common Between a Drop of Water and an Atomic Nucleus? 236
The Puzzle of Particle Interaction 238
The Elusive Neutrino 239

Chapter XIV

THE LATEST ON NUCLEAR STRUCTURE

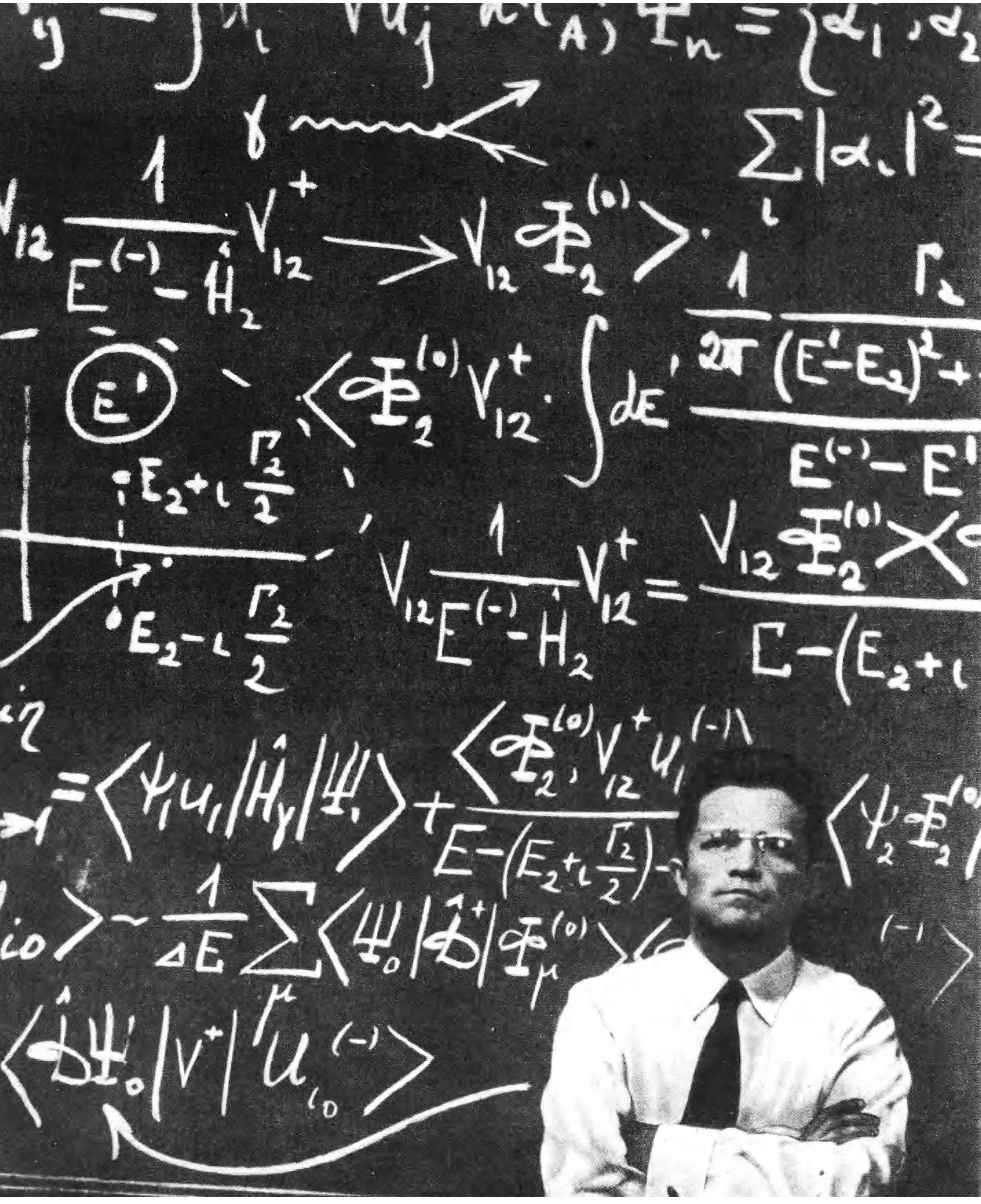
What is a Nuclear 'Model'? 243
When is a Light Projectile Better Than a Heavy One? 245
Regularities of Electron Showers 248

Small-Calibre Atomic 'Artillery' 249
New Discoveries, New Models 250
Can We See Atoms? 251
How They Peeped Inside a Proton 254

Chapter XV
COMPETITION WITH SPACE
Cosmic Rays 257
About 'Electron-Asses', 'Dirac's Sea', Anti-Particles, and Other Obscure Things 261
The First Anti-Particle—The Positron 262
There Should Also Be an Anti-Proton 263
Can Anti-Matter Exist? 268
Are There More Symmetries in the World of Microparticles? 268
How 'Elementary' are Elementary Particles? 270
Can a Part Be Larger Than the Whole? 271
When Two Times Two Is Too Much 274

Chapter XVI
ARTIFICIAL ATOMS
The Positronium, an Artificial Atom 282
Two Photons or Three? 282
Why Spin Is Also Important 283
The Mesonic Atom 285

Chapter XVII
CAN THE HYDROGEN BOMB BE TAMED?
What About Making Small Change? 289
The 'Scream' of Colliding Galaxies 290
Plasma, the Fourth State of Matter 291
The Miraculous Spark 295
The Energy of a Waterfall in a Glass Tube 297
A 'Personage' with a Thousand Whims 299
A Magnetic 'Cage' for a 'Firebird' 300
If Only... 303



Chapter One

ON THE EVE OF A GREAT DISCOVERY

A Dream of the Impossible

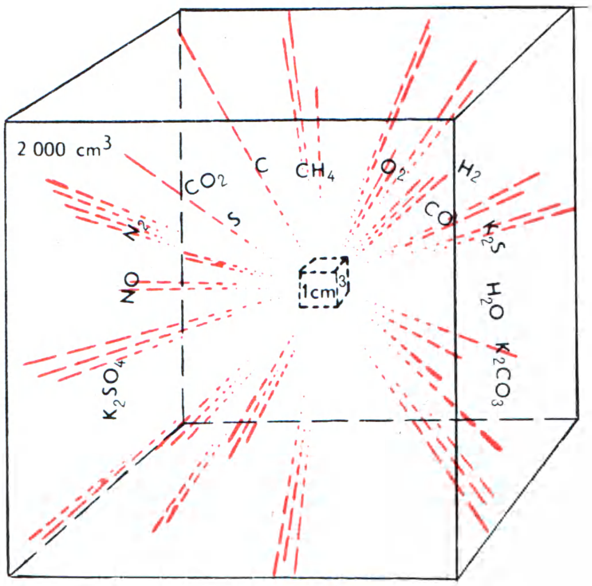
The end of the nineteenth century and the beginning of the twentieth were exceptionally rich in breath-taking discoveries and inventions.

This tempestuous burgeoning of knowledge was accompanied with a flood of amazing stories that attempted to forecast the future development of science and technology, or at least to outline distant but ardently desired goals. In them we find everything that men have ever dreamed about: a gigantic, palatial submarine ploughing the seas and oceans of the world at unprecedented speed and capable of sailing to the Pole even below ice a thousand kilometres thick; flying machines of the most amazing design capable of carrying men non-stop from continent to continent and around the world; rockets carrying bold investigators to other worlds in the Universe; apparatus making it possible to converse over long distances without wires and to see your interlocutor.

People discovered miraculous preparations that converted timid rabbits rapidly into giants, and finally a mysterious chemical, a matchboxfull of which would produce enough power to propel a large ship for many years.

The actual development of science and technology in many ways outran the fervid fantasies of the writers and the dreams and conjectures of the boldest scientists.

We have long been used to talking without excitement of huge multi-engined aircraft that can fly non-stop halfway round the Earth and carry around seven hundred people, or a payload of 80 tons, and of real submarine cruisers. We freely employ radio, the brilliant invention of the Russian scientist A. S. Popov. And in our homes, alongside thousands of customary things, stand television sets that enable us to see across great distances.



What happens when gunpowder explodes

In this time new sources of energy have been discovered that have made it possible to build engines of a quite new kind, to extend the range of aircraft several times over, and to propel multiton rockets thousands of kilometres at undreamed-of speeds, even to send them to the Moon, and Venus, and Mars, and around the Sun. And various explosives have been invented that enable a small projectile to pierce thick armour.

Only the tiny source of almost inexhaustible energy imagined by writers, still remained an inaccessible dream despite the efforts of a whole army of scientists.

Over thousands and thousands of years, through encountering the most diverse substances and transformations at every step, man gained experience of releasing the energy in them. And that experience indicated unambiguously that whatever incredible transformations matter underwent, the energy released could not be very great. Even explosions released relatively little.

It took enormous labour for chemistry, the exact and ordered science of the properties and transformations of matter, based on a host of facts and discoveries and crowned by Mendeleev's prescient Periodic Table of the elements, to make its way. This science seemed to have exhaustively established, with no room for illusion, that in all the chemical transformations of matter in the world around us in which there is a release of energy, complex substances are always and invariably converted into simple ones, and vice versa.

The burning of ordinary gunpowder is a violent, almost instantaneous chemical reaction between two molecules of potassium nitrate, an atom of sulphur, and three atoms of hydrogen, resulting in the formation of one molecule of potassium sulphate, one molecule of nitrogen, and three molecules of carbon dioxide.

Calculation of the energy released by all these chemical reactions, even the most violent, showed the miraculous matchbox, capable of releasing tremendous amounts of energy, to be inaccessible, and seemingly predestined to remain the most fruitless of all human quests. In fact, one kilogram of the best fuel was enough to drive a very small locomotive several hundred metres or a motor car ten or twelve kilometres; one kilogram of the most powerful explosive would propel a shell weighing one kilogram ten or fifteen kilometres. In order to drive trains and steamships, fly aircraft, and fire huge guns, it was necessary to use large quantities of fuel — thousands of tons of coal, hundreds of tons of oil, scores of tons of petrol, hundreds of kilograms of gunpowder or dynamite.

All down the ages of his struggle with nature man has never seen the wonder of a stove that would heat his dwelling for a whole long winter night on a single chip of wood, or been able to fight

and win a many-days battle with a handful of gunpowder. Nevertheless the idea of its being possible to obtain inexhaustible power from a tiny amount of matter has lived in the secret thoughts not just of the writers of amazing stories but also of the many scientists who have tried for ages to penetrate the mysteries of the structure of the matter around us.

'Plum Pudding'

Before embarking on our narrative, let us just glance at what was known about the structure of matter at the turn of the present century.

It had been established beyond all doubt that the world around us, both dead and living, consisted of various combinations of a relatively small number of basic chemical elements, beginning with the lightest, hydrogen, and ending with the heaviest, uranium; but not all the elements known to us now had then been discovered.

Some chemical elements are found in nature in pure form, like native silver, gold, carbon, copper, and so on, but most occur in mixtures or compounds with other elements.

The atom had been shown to be the smallest, and hence indivisible, particle of an element.

The molecule was considered to be the smallest particle of a substance consisting of one or more elements that still preserved the properties of that substance. When molecules were split they broke down into their constituent atoms and the properties of the original substance were lost.

Any chemical reaction or transformation, even the most complex, could only enable one at best to isolate pure elements, or to create new combinations of elements. Since gold is a pure (or noble) element, its atoms remain unchanged, without chemical transformation, which is why all the attempts of mediaeval alchemists to convert some elements into others, and in particular mercury and lead into gold, proved vain.

Development of knowledge of electricity led first to the idea that it was 'particulate' and then to the revolutionary discovery by the eminent British physicist, Prof. J. J. Thomson, of the smallest particle of negative electricity, the electron, or as it was then called, the atom of electricity.

Soon Robert Millikan in the USA succeeded in determining the mass or weight of an electron. It turned out to be $9.10904 \cdot 10^{-28}$ gram, 1836 times as light as an atom of hydrogen, the lightest of all the known elements.

Scientists supposed the indivisible atom to be a sphere uniformly charged with positive electricity, in which electrons were embedded. 'Something like plum pudding', Prof. J. J. Thomson once said, and in 1898 he suggested such a model for the atom. The total negative charge of its electrons was always equal to the positive charge of the sphere, i.e. the atom as a whole was neutral and only by losing one or more electrons did it become positively charged, and form what is called a positive ion.

With a few modifications that was the idea of atomic structure at the end of the nineteenth century; and although it introduced a certain order much was still not clear. The electron apart, what was the rest of the positively charged mass of the atom? Were there positively charged particles in it like electrons? These and some other questions were still unresolved.

Then, in the harmoniously constructed system of that time, a substance was found that behaved quite differently from all known matter. It did not, seemingly, obey the immutable laws go-

PERIODIC TABLE OF THE ELEMENTS

Groups →	I	II	III		IV	V
2	3 Li Lithium 6.939 (1 2)	4 Be Beryllium 9.0122 (2 2)	5 B Boron 10.811 (3 2)		6 C Carbon 12.01115 (4 2)	7 N Nitrogen 14.0067 (5 2)
3	11 Na Sodium 22.9898 (1 8 2)	12 Mg Magnesium 24.312 (2 8 2)	13 Al Aluminium 26.9815 (3 8 2)		14 Si Silicon 28.086 (4 8 2)	15 P Phosphorus 30.9738 (5 8 2)
4	19 K Potassium 39.102 (1 8 8 2)	20 Ca Calcium 40.08 (2 8 8 2)	21 Sc Scandium 44.956 (2 9 8 2)		22 Ti Titanium 47.90 (2 10 8 2)	23 V Vanadium 50.942 (2 11 8 2)
	29 Cu Copper 63.546 (1 18 8 2)	30 Zn Zinc 65.37 (2 18 8 2)	31 Ga Gallium 69.72 (3 18 8 2)		32 Ge Germanium 72.59 (4 18 8 2)	33 As Arsenic 74.9216 (5 18 8 2)
5	37 Rb Rubidium 85.47 (1 8 18 8 2)	38 Sr Strontium 87.62 (2 8 18 8 2)	39 Y Yttrium 88.905 (2 9 18 8 2)		40 Zr Zirconium 91.22 (2 10 18 8 2)	41 Nb Niobium 92.906 (1 12 18 8 2)
	47 Ag Silver 107.868 (1 18 18 8 2)	48 Cd Cadmium 112.40 (2 18 18 8 2)	49 In Indium 114.82 (3 18 18 8 2)		50 Sn Tin 118.69 (4 18 18 8 2)	51 Sb Antimony 121.75 (5 18 18 8 2)
6	55 Cs Cesium 132.905 (1 8 18 18 8 2)	56 Ba Barium 137.34 (2 8 18 18 8 2)	57 La Lanthanum 138.91 (2 9 18 18 8 2)	* 58–71	72 Hf Hafnium 178.49 (2 10 32 18 8 2)	73 Ta Tantalum 180.948 (2 11 32 18 8 2)
	79 Au Gold 196.967 (1 18 32 18 8 2)	80 Hg Mercury 200.59 (2 18 32 18 8 2)	81 Tl Thallium 204.37 (3 18 32 18 8 2)		82 Pb Lead 207.19 (4 18 32 18 8 2)	83 Bi Bismuth 208.980 (5 18 32 18 8 2)
7	87 Fr Francium [223] (1 8 18 32 18 8 2)	88 Ra Radium [226] (2 8 18 32 18 8 2)	89 Ac Actinium [227] (2 9 18 32 18 8 2)	** 90–103	104 Ku Kurchatovium (2 10 32 32 18 8 2)	105

58 Ce Cerium 140.12 (2 8 20 18 8 2)	59 Pr Praseodymium 140.907 (2 8 21 18 8 2)	60 Nd Neodymium 144.24 (2 8 22 18 8 2)	61 Pm Promethium [145] (2 8 23 18 8 2)	62 Sm Samarium 150.35 (2 8 24 18 8 2)	63 Eu Europium 151.96 (2 8 25 18 8 2)	64 Gd Gadolinium 157.25 (2 9 25 18 8 2)
90 Th Thorium 232.038 (2 10 18 32 18 8 2)	91 Pa Protactinium [231] (2 9 20 32 18 8 2)	92 U Uranium 238.03 (2 9 21 32 18 8 2)	93 Np Neptunium [237] (2 9 22 32 18 8 2)	94 Pu Plutonium [242] (2 8 23 32 18 8 2)	95 Am Americium [243] (2 8 25 32 18 8 2)	96 Cm Curium [247] (2 9 25 32 18 8 2)

Mendeleev's Periodic Table of Elements

VI	VII	VIII	Periods		
	H 1 1.00797 Hydrogen (1)	He 2 4.0026 Helium (2)	1	He — s-elements; Ne — p-elements; Hg — d-elements; Td — f-elements	
O 8 15.9994 Oxygen (6 2)	F 9 18.9984 Fluorine (7 2)	Ne 10 20.183 Neon (8 2)	2		
S 16 32.064 Sulphur (6 8 2)	Cl 17 35.453 Chlorine (7 8 2)	Ar 18 39.948 Argon (8 8 2)	3		
Cr 24 51.996 Chromium (1 13 8 2)	Mn 25 54.9380 Manganese (2 13 8 2)		Fe 26 55.847 Iron (2 14 8 2)	Co 27 58.9332 Cobalt (2 15 8 2)	Ni 28 58.71 Nickel (2 16 8 2)
Se 34 78.96 Selenium (6 18 8 2)	Br 35 79.904 Bromine (7 18 8 2)	Kr 36 83.80 Krypton (8 18 8 2)	4	Atomic masses and mass-numbers of longest-lived isotopes (in brackets) are International 1965 values	
Mo 42 95.94 Molybdenum (1 13 18 8 2)	Tc 43 [99] Technetium (2 13 18 8 2)		Ru 44 101.07 Ruthenium (1 15 18 8 2)	Rh 45 102.905 Rhenium (1 16 18 8 2)	Pd 46 106.4 Palladium (18 18 8 2)
Te 52 127.60 Tellurium (6 18 18 8 2)	I 53 126.9044 Iodine (7 18 18 8 2)	Xe 54 131.30 Xenon (8 18 18 8 2)	5		
W 74 183.85 Tungsten (2 12 32 18 8 2)	Re 75 186.2 Rhenium (2 13 32 18 8 2)		Os 76 190.2 Osmium (2 14 32 18 8 2)	Ir 77 192.2 Iridium (2 15 32 18 8 2)	Pt 78 195.09 Platinum (1 17 32 18 8 2)
Po 84 [210] Polonium (6 18 32 18 8 2)	At 85 [210] Astatine (7 18 32 18 8 2)	Rn 86 [222] Radon (8 18 32 18 8 2)	6		
106					

Mass number of longest-lived isotope

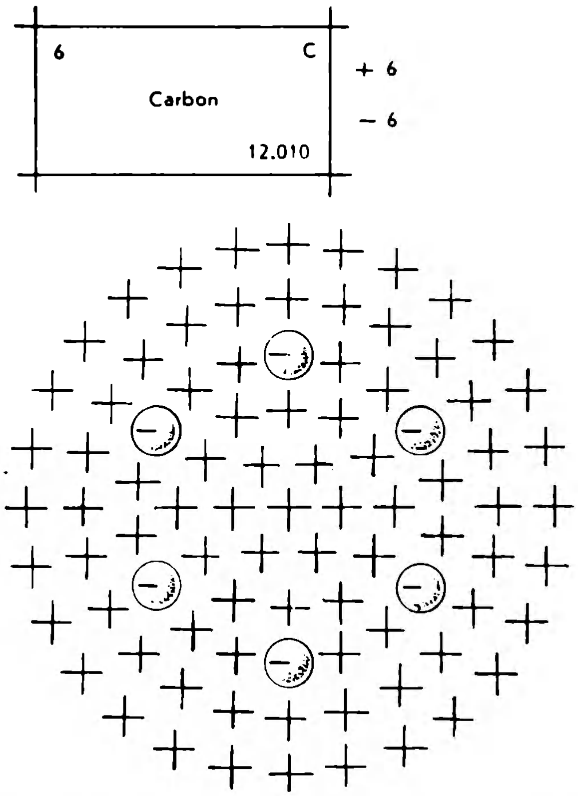
Atomic number (number of electrons in atom)

Number of electrons in shell

84 [210] Po (6 18 32 18 8 2)

Atomic mass (C^{12}=12 scale)

158.924 65 Tb Terbium (2 8 27 8 2)	162.50 66 Dy Dysprosium (2 8 28 18 8 2)	164.930 67 Ho Holmium (2 8 29 18 8 2)	167.26 68 Er Erbium (2 8 30 18 8 2)	168.934 69 Tm Thulium (2 8 31 18 8 2)	173.04 70 Yb Ytterbium (2 8 32 18 8 2)	174.97 71 Lu Lutetium (2 9 32 18 8 2)
[247] 97 Bk Berkelium (2 9 26 32 18 8 2)	[249] 98 Cf Californium (2 9 27 32 18 8 2)	[254] 99 Es Einsteinium (2 9 28 32 18 8 2)	[253] 100 Fm Fermium (2 9 29 32 18 8 2)	101 Md Mendelevium (2 9 30 32 18 8 2)	102 (No) Nobelium (2 9 31 32 18 8 2)	103 Lr Lawrencium (2 9 32 32 18 8 2)



This is how Thomson envisaged the structure of the atom in 1898

verning all other matter and went against the generally accepted view of the indivisibility of the atom.

Becquerel's Mistake

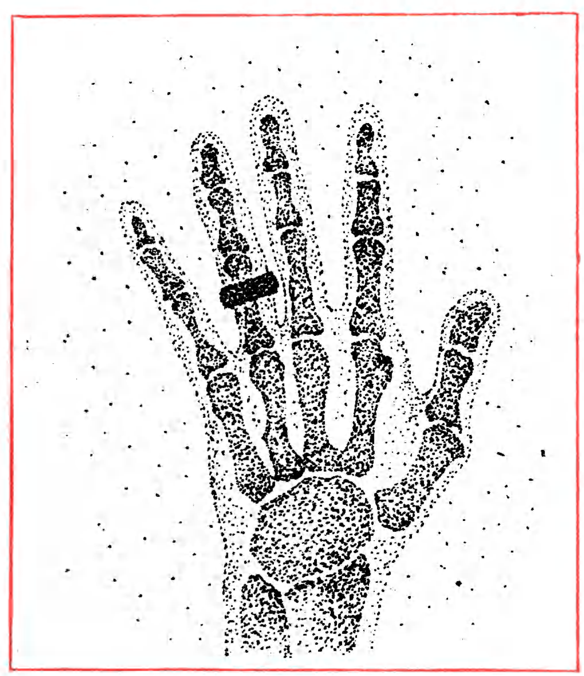
It happened at the very beginning of 1896. Only several months before the German scientist W. C. Roentgen had made the startling discovery that immortalized his name, the rays, now known as Roentgen rays or more commonly as X-rays. These rays passed freely through paper, wood, and the human body, and even through thin metal sheets. A photographic plate exposed in darkness to this invisible radiation, darkened as when exposed to rays of sunlight.

Scientists in all countries feverishly repeated Roentgen's experiment, and studied the new rays and the phenomena associated with them.

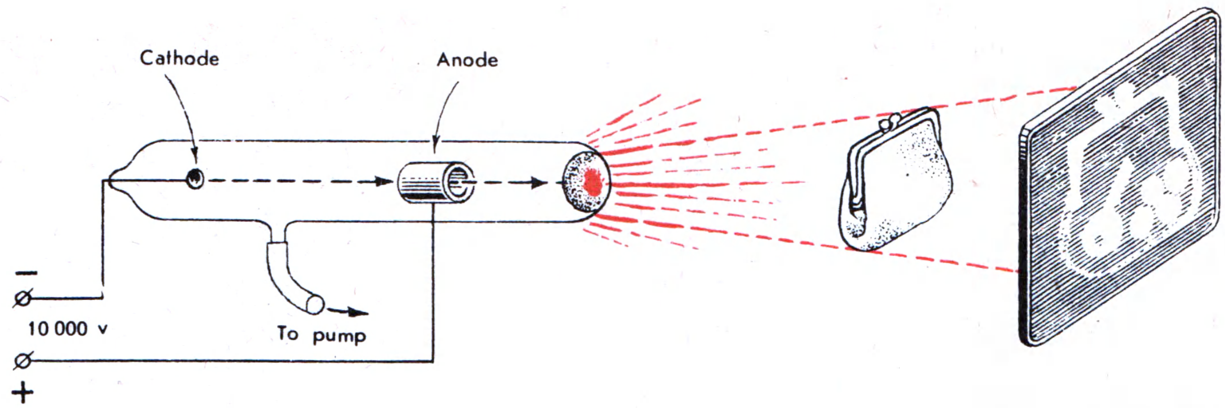
In the first tube used by Roentgen the mysterious penetrating rays emerged from a definite section of the tube and during the experiment a small greenish-yellow spot glowed on the glass opposite it. Neither Roentgen himself nor other scientists were able to explain the reason for this luminescence.

The phenomenon of the luminescence of certain substances exposed to sunlight, known as fluorescence, had long been known and the French scientist Henri Becquerel had spent many years studying it.

The fluorescence appearing on the glass of Roentgen's tube attracted Becquerel's attention and, after studying the performance of the tube in detail he became convinced that it was this fluorescence that caused the emission of the new rays. Then, all other fluorescent substances must also emit similar rays, some weaker and others stronger. Before Roent-



The experiment that led to the discovery of X-rays



X-rays passing through a non-transparent solid left traces on a photographic plate

gen, no one had studied the phenomenon, and the connection between the phenomena had not been observed.

Wishing to check his deductions, Becquerel carefully wrapped a photographic plate in black paper and placed on it the first piece of fluorescent material that came to hand, which fluoresced strongly when exposed to sunlight. If the assumption were correct that a fluorescent substance exposed to brilliant sunshine emitted not only visible light but also Roentgen's invisible rays, then these rays would certainly pass through the layers of black paper and expose the photographic plate. But if there were no Roentgen rays nothing would be imprinted on the plate since it was well protected against all visible light by the layers of its wrapping of black paper.

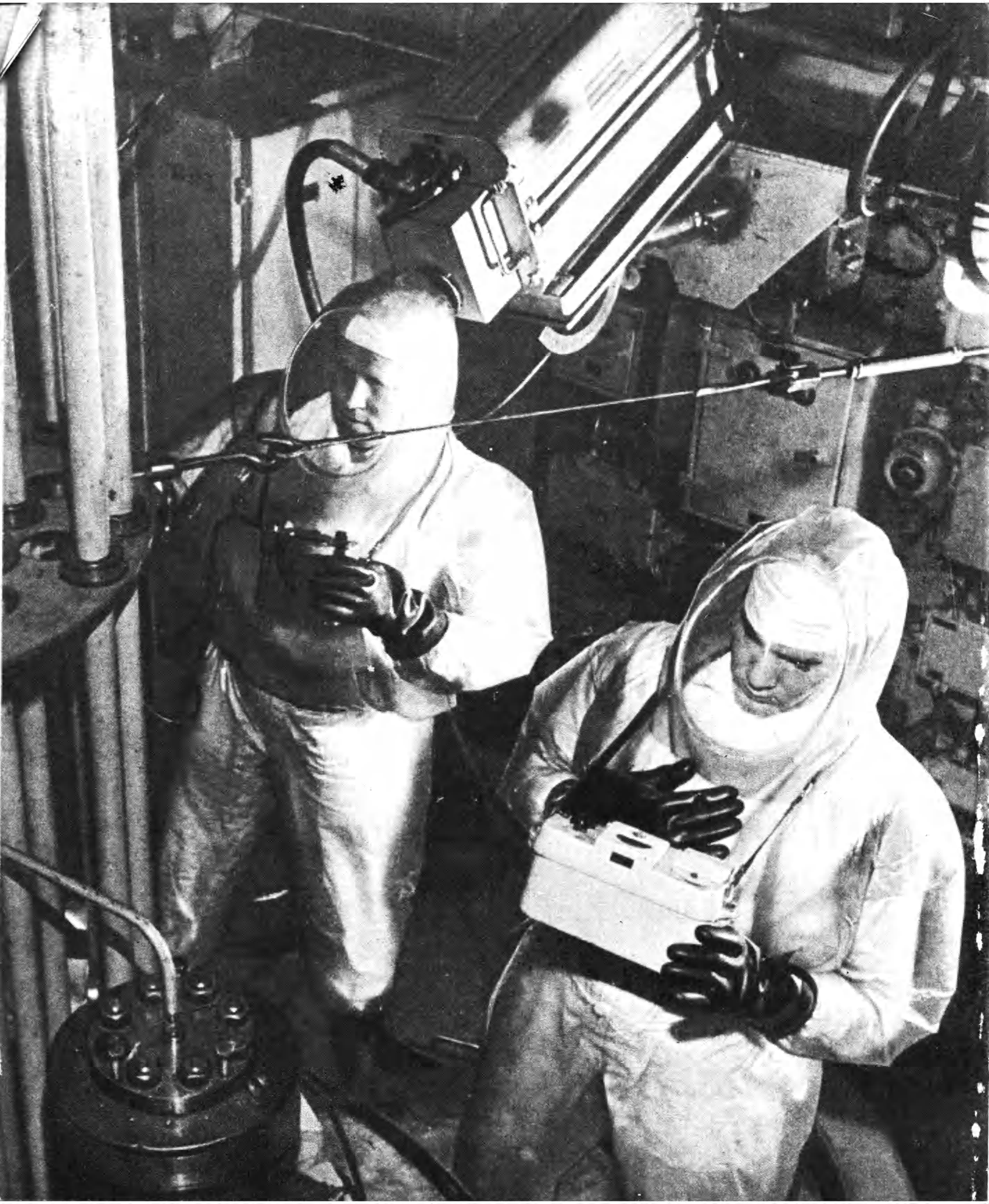
The fluorescent substance picked up at random and exposed to bright sunshine happened to be a binary salt, sulphate of potassium and uranium. The experiment succeeded as never before. When he developed the plate a few hours later Becquerel detected a clear imprint on it of his piece of uranium salt. He repeated the experiment several times and prepared an article about his discovery for publication. But being a scrupulous scientist, with an exacting attitude to the results of his own experiments, especially when successful, Becquerel decided to repeat them again, carefully checking the minutest details.

His shattering discovery would never have been made for a long time to come if the triumphant Becquerel had limited himself just to his first series of experiments, which seemed to confirm his guess so fully and completely.

The weather had become cloudy and the sun did not penetrate the leaden thickness. The wrapped plate and the piece of uranium were put away in a drawer. Some days later Becquerel decided in any case to develop the plate. To his astonishment the image of the salt on the plate was even sharper and clearer than in the first experiments, although the uranium could not have fluoresced in the darkness of the drawer, still less in cloudy weather.

Several additional experiments proved sufficient to establish beyond dispute that the binary salt of uranium and potassium emitted invisible rays that resembled Roentgen's rays, whether it was exposed to sunlight or kept in darkness.

Thus, on 26 February 1896, a new physical phenomenon was discovered for humanity, the emanation by uranium salts of invisible penetrating rays resembling Roentgen's rays. It was destined to become the starting point of the whole new physics of the twentieth century.



Chapter Two

RADIOACTIVITY

A Polish Girl's Discovery

Becquerel's discovery attracted the attention of scientists the whole world over. The existence of penetrating rays emitted by a natural mineral was something utterly incomprehensible and really mysterious.

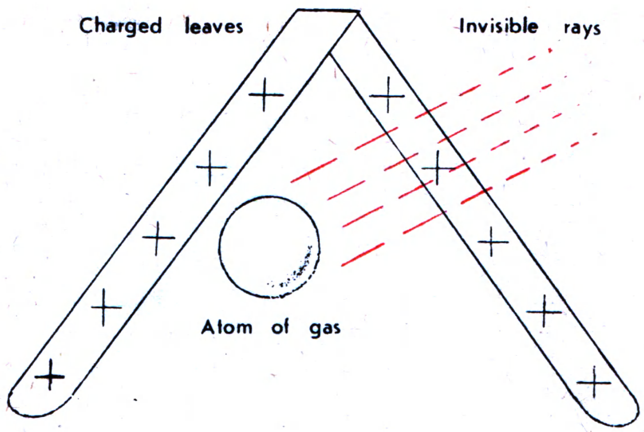
Among the scientists intrigued by this so very unusual phenomenon was a Polish girl, a talanted young French chemist working in Becquerel's laboratory in Paris, Marie Sklodowska, married to Pierre Curie.

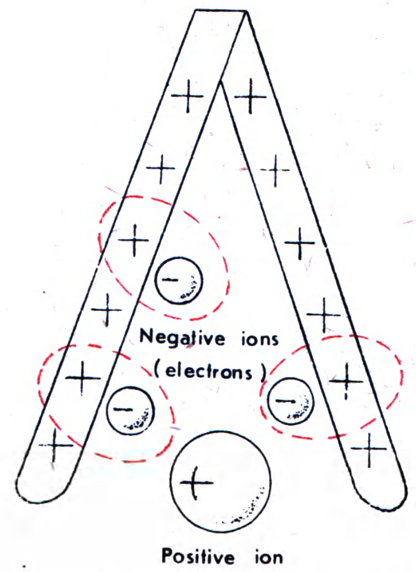
The photographic plate darkening under the action of the unknown rays had served its purpose in their discovery. But many delicate experiments were required before their nature could be explained; and it was necessary to find other methods of investigation.

And that was where Marie Sklodowska-Curie began.

It was known that atmospheric nitrogen and oxygen lost one or more electrons and became positively charged ions when exposed to Roentgen's rays. Owing to the presence of positive ions and electrons separated from atoms (free electrons) the air became a conductor of electricity. In such ionized air charged bodies could not long retain their charges and quickly lost them.

Ionization of the air was easily detected by means of that well-known school instrument, the electroscope. A metal rod is secured in a plug made of material that does not conduct electricity. To the bottom of the rod a thin leaf of aluminium foil is attached which can deflect to one side or the other. And on the side of the rod is fixed a scale from which the angle of deflection of the foil can be read. When a charged body is brought into contact with the upper part of the rod, both the rod itself and the attached foil become charged. And since like charges repel, the light





An ordinary school electroscope is a very useful and exact instrument for a number of physical investigations. When it is charged the leaves spread apart. When the instrument is exposed to X-rays the air around it is ionized and becomes a conductor, with the result that the leaves are discharged and return to their original vertical position

flexible leaf of foil is deflected to an extent depending on the strength of the charge applied. (There are also electroscopes of other designs, for example, one with two flexible leaves of foil on the end of the rod.)

But if a beam of X-rays is directed at the electroscope, or a substance emitting the rays discovered by Becquerel is brought near it, the foil quite quickly falls back toward the rod, that is to ay, the electroscope is discharged. And the more ions are formed in the air near the charged rod the quicker the instrument is discharged.

Such was the instrument, only more intricate and of improved construction, that Marie Sklodowska-Curie used.

For a long time she investigated every substance available known to contain uranium. As was to be expected, it turned out that the more uranium it contained the stronger was its ionizing effect, and the electroscope was discharged most quickly by rays emanating from pure metallic uranium.

Soon Marie Curie encountered her first unexpected result. One of the natural uranium minerals, pitchblende from the Austrian town of Joachimsthal (now Jachymov in Czechoslovakia), turned to be a much stronger emitter than the purest uranium.

There was nothing for it but to suppose that pitchblende and torbernite contained some other, still unknown substance with a higher capacity than uranium to emit rays.

The property of matter spontaneously to emit invisible radiation Marie Sklodowska-Curie called 'radioactivity' (from the Latin *radius*, meaning ray).

In her search for these puzzling irradiating substances Marie was joined by her husband Pierre Curie, who devoted himself wholly to this new, entrancing task. After nearly two years of hard work in incredibly difficult conditions, during which they had to process several tons of uranium ore placed at their disposal, Marie and Pierre Curie finally, in July 1898, obtained a small quantity of a strongly radioactive compound of bismuth that contained a hitherto un-

known element, which they called polonium in honour of Marie's native country.

Further surprises followed, one after another.

After polonium they succeeded, in December 1898, in detecting and separating a chlorine compound containing another and still stronger radioactive substance, which they called radium, meaning radiant.

And finally, after another two years, and after 45 months from the beginning of their persistent work, the Curies obtained 0.1 gram of radium chloride and succeeded in separating a grain of pure metallic radium from it. Its radioactivity was a million times that of radioactive uranium.

Radium proved to be a truly amazing substance. It rapidly darkened photographic plates, even when covered by a thick layer of lead quite impervious to the passage of X-rays. Radium salts emitted a soft, bluish light. Radium rays, just like Roentgen's rays, made screens coated with zinc sulphide, barium platinocyanide, and other substances, glow in the dark. Minute quantities of radium, less than a thousand millionth of a gram in weight, could be detected by the intense ionization caused by their emanation. Under its action pure clear white glass took on various colours.

Something else unexpected was discovered: radium had a strong effect on living organisms and its radiation was downright dangerous to man. Its first victim was Henri Becquerel himself. One day, as he was getting ready to give a lecture, he put a small vial of radium salt into his waistcoat pocket. A few hours later a bad burn developed on the skin underneath; the burn later developed into an ulcer that did not heal for several months.

And yet another peculiarity distinguished radium sharply from all other then known substances. It always, as Pierre Curie noted, had a rather higher temperature than the medium around it. Measurements showed that one gram of radium gave off around 136 calories of heat per hour,* which is sufficient to raise the temperature of a 200-gram beaker of water in approximately six days from 0°C to 100°C.

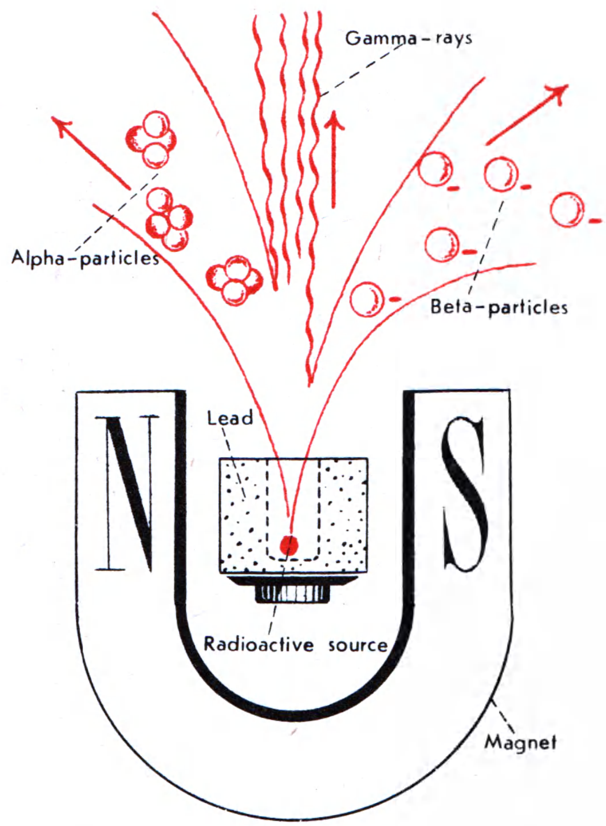
And it was most interesting that the radiating radium did not lose weight. Here was a new, quite inconceivable and unknown source of energy.

When several more radioactive substances had been found study of this new type of ray began. The following simple experiment, among others, was made. In order to ascertain whether the mysterious radiation was a flux of charged particles a narrow beam from a radioactive source was passed between the poles of a strong magnet, since it was known that the path of charged particles was distorted by a magnetic field. The scientists' assumption was confirmed. The beam split up into three parts.

The rays that were least deflected were named alpha-rays. The part of the radiation that was most easily deflected, and in the opposite direction from the alpha-rays, were called beta-rays, while those that were not deflected at all were called gamma-rays.

Each of these types of radiation began to be studied separately. It turned out that they were absorbed differently by various substances. An ordinary sheet of paper or thin fabric absorbed alpha-rays completely. Beta-rays proved to have greater penetrating power and could easily pass through a sheet of aluminium several millimetres thick. But

* A calorie (cal) is the quantity of heat required to raise the temperature of one gram of water one degree centigrade. A large calorie (cal) contains 1000 cal.



Through the effect of a magnetic field the seemingly uniform rays of radioactive substances divide into three parts

further investigation showed that gamma-rays had the greatest force of all. It took a sheet of lead tens of centimetres thick to arrest them.

Alpha-rays proved to be a flux of rapidly moving, positively charged particles (alpha-particles), about 7000 times heavier than electrons. Because their mass was so much greater they were not deflected in a magnetic field as strongly as electrons, their velocity in a magnetic field was much slower and they were deflected as strongly by it as electrons.

The eminent British scientist Ernest Rutherford succeeded in showing by very delicate and clever means that alpha-particles were nothing but double-ionized atoms of helium, that is to say helium atoms that had lost two of their electrons so that they had two positive charges. A tiny piece of radium was put into a glass vessel with double walls, the space between which had been carefully evacuated of air. The thickness of the walls was such that alpha-particles emitted by the radium passed easily through the inner, thinnest one, but could not penetrate the outer one. After several days an appreciable amount of helium gas was noticed in the space between the two walls.

To observe individual alpha-particles Rutherford used another instrument just as simple, the spinthariscope, invented by the English physicist Sir William Crookes. A needle with a minute amount of radium salt on its point is placed inside a tube in front of a fluorescent screen made of zinc sulphide. The other end of the tube is closed by a magnifying glass. As soon as an alpha-particle hits the screen the latter begins to glow and the luminescence is seen through the lens. The observer sees a very beautiful picture—a multitude of small bright stars glow and twinkle against the dark background.

By measuring the charges and masses of beta-rays it was shown that they were the carriers of negative charges, electrons, already known to science. They began to be called beta-particles.

The gamma-rays which had exposed Becquerel's photographic plate (alpha-rays were absorbed by the wrapping) proved to be electromagnetic oscillations, like Roentgen's rays. They were propagated in a vacuum with the velocity of light, 300 000 kilometres per second.

Gamma-rays are very dangerous to humans and animals. Their energy is only appreciably attenuated by increase of distance, through expenditure on ioniznig atoms and molecules of the matter around them.

The Radioactive Families

But what happens to the radioactive atoms themselves? What mysterious changes do they undergo in emitting alpha- and beta-particles and gamma-rays?

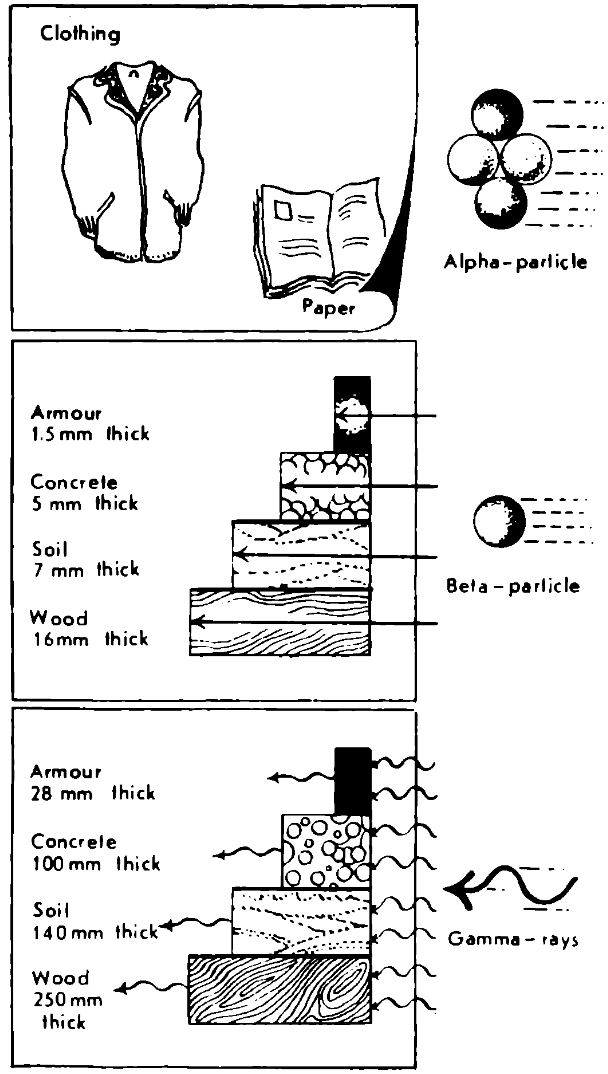
The answers were given jointly by Rutherford and the famous British physicist Frederick Soddy. They suggested that the atoms of radioactive substances, unlike those of ordinary elements, were not simple stable formations. They could break down spontaneously and through emitting definite particles were transformed into other elements. Thus, through emitting alpha-particles, radium atoms were converted into atoms of the radioactive gas radon. As a result atoms of two other new elements—radon and helium—were formed.

That, however, was not the end of the process of radioactive decay. The newly formed radon in its turn also emitted alpha-particles and was converted into a new substance, radium A, which is also radioactive and in turn is converted into radium B, and the latter into another element, and so on.

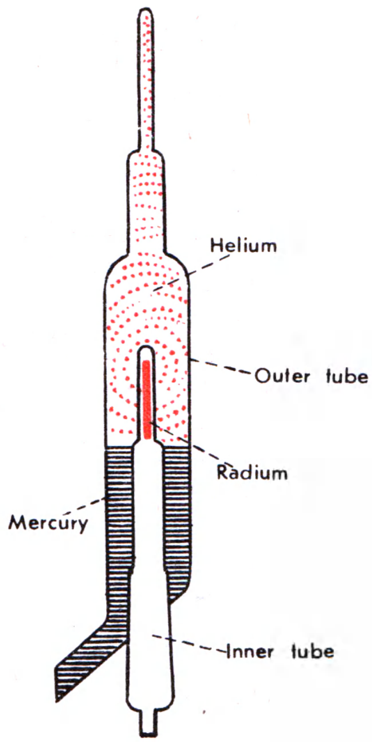
The process of radioactive breakdown only ceases when the entire quantity of radium has been converted into ordinary lead, which we all know.

It was no accident that radium was found in uranium ores. It had all been formed some time or other from uranium and continued to be formed in all ores that contained the slightest trace of that element.

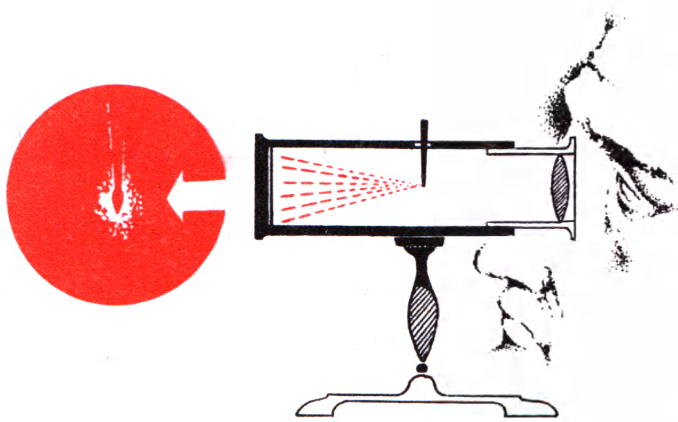
But another question arises here. Why do the radioactive substances studied by scientists give off all three kinds of radiation while, to judge from what we have just said, they should only emit alpha-particles? The fact is that in addition to the main emitter, the radioactive substances studied usually also contain substances that are formed in



The ability of the particles and rays emitted by radium and polonium to penetrate substances proved to be different



This elegant experiment succeeded in establishing that alpha-rays were strongly ionized atoms (lacking all their electrons) of helium gas



The spinthariscope, a physical instrument first sold as a curiosity and amusing toy

their turn from them, and other substances formed from the numerous products of successive breakdowns accompanied with the emission of these particles and rays. That is why uranium radiation proved so complicated, containing as it does its own breakdown particles and those of radium, radon, radium A, etc.

And even when it is possible to eliminate the substances that serve as it were as the forebears of the substance being studied there are the others that it forms which it is very difficult to eliminate, since they keep appearing continuously during the decay of the radioactive substance.

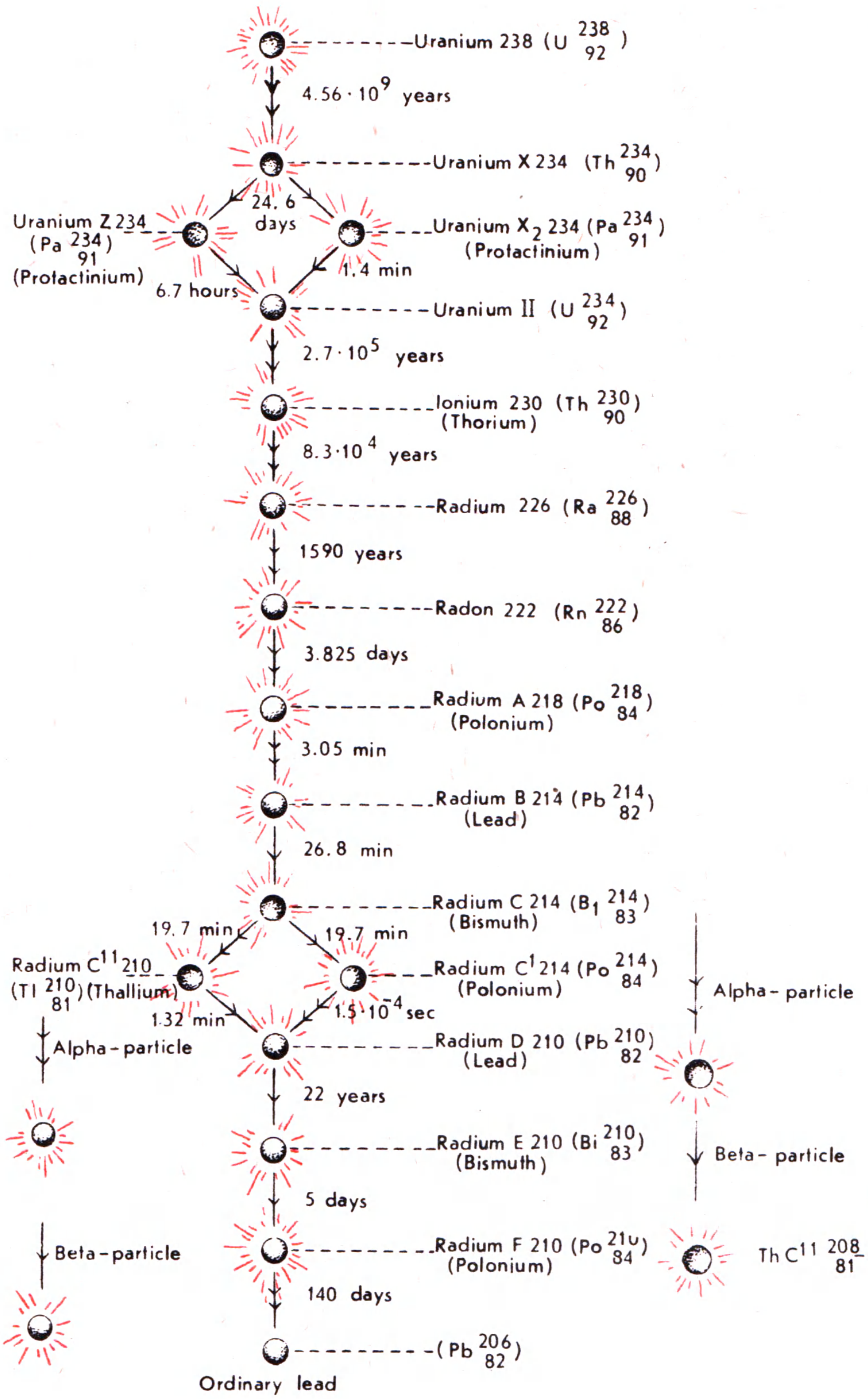
The chain of these elements that are gradually formed one from the other, are called a radioactive series or family. There are three such series, embracing all the known heavy radioactive elements and all ending finally in ordinary lead.

Study of these chains shows that all natural heavy radioactive elements, in breaking-down, give off either alpha-particles or electrons (beta-particles). Gamma-rays, as a rule, accompany the radiation of beta-particles.

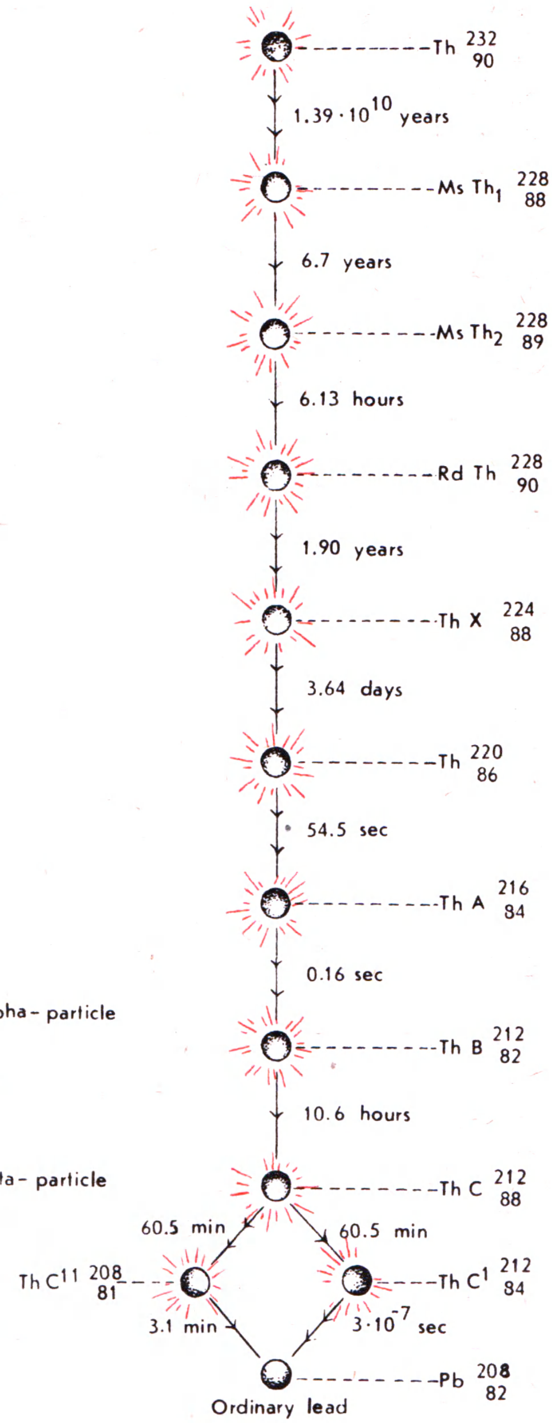
In certain cases a more intricate phenomenon takes place, when one and the same element breaks down in two different ways, emitting either alpha-particles or electrons. This branching type of breakdown is known as forked decay, but it is the exception rather than the rule in breakdown chains.

It took several decades of painstaking investigations to determine the laws of radioactive decay and find the most successful means of measuring its course.

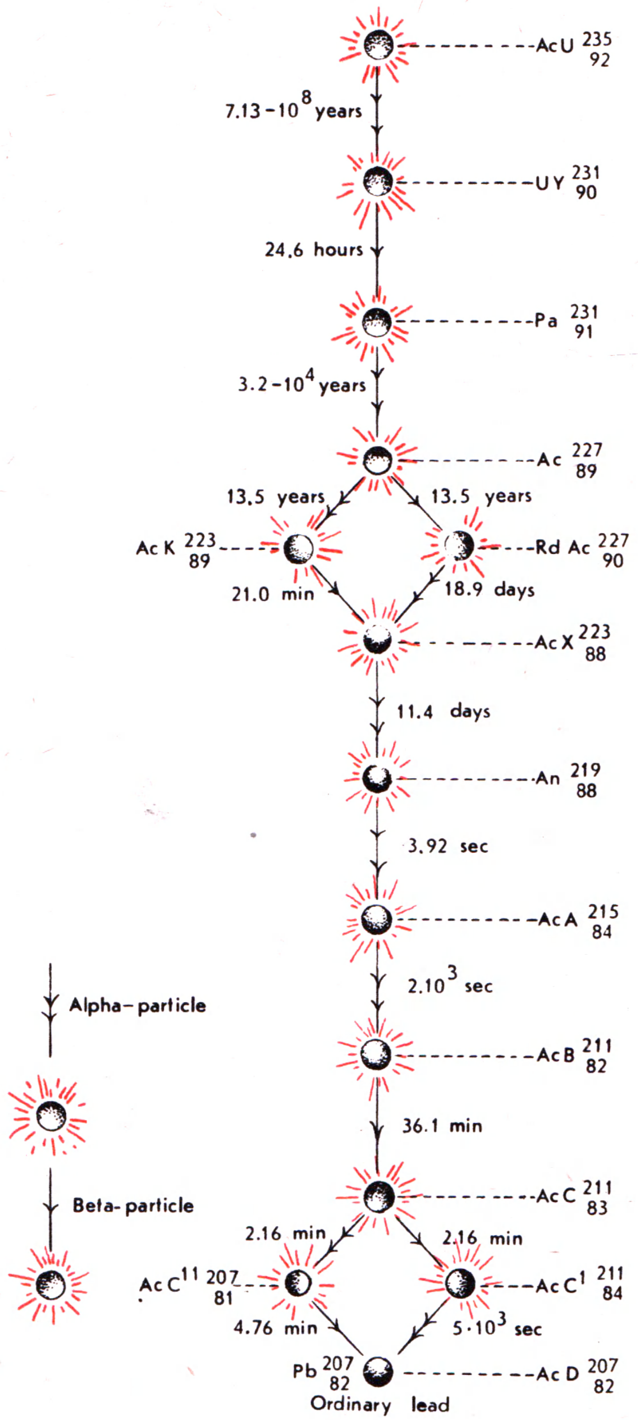
The main quantity characterizing a radioactive substance is its half-life or half-value period. When we say, for example, that the half-life of a substance is four days, we mean that it takes



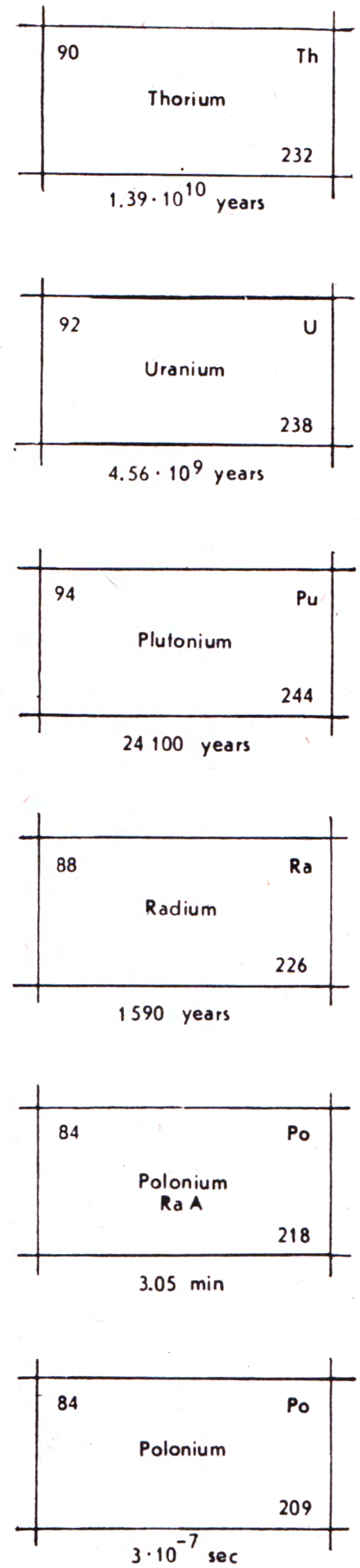
The radioactive family of uranium, showing the sequence of its conversion into other elements



The radioactive family of thorium



The radioactive family of actinium



How the half-lives of various radioactive substances differ

four days for half the original amount of the substance to disintegrate and turn into other elements. During the next four days half the remaining amount disintegrates, so that after eight days only a quarter of the original amount remains, and after twelve days one-eighth, and so on. In other words, for the radioactivity of any substance to fall to 1 per cent of the initial amount, seven half-lives must elapse. But it must be remembered that this is only the average rate of decay of a radioactive substance. In fact some atoms do not disintegrate during the whole period the substance exists while other atoms may break down almost immediately or in a much shorter interval of time.

The more intensively a substance disintegrates the shorter is its half-life, which is why the life of strong emitters is relatively short. One gram of uranium contains around $2.5 \cdot 10^{21}$ atoms; of that amount a total of around 12 000 atoms disintegrates in one second. The half-life of uranium is therefore exceptionally long, around 5 000 million years! The half-life of radium is 1590 years, of radon a few days, of radium A a few minutes, of polonium-212 $3 \cdot 10^{-7}$ second, and so on.

Almost all natural radioactive elements are the heaviest ones in the Periodic System. And because of their spontaneous decay they are also the most unstable.

The numerous experiments made with radioactive substances yielded yet another unexpected result. While no efforts could smash the atoms of stable elements, radioactive elements on the contrary broke down spontaneously and no force in the world, neither temperatures close to absolute zero or the highest obtainable on Earth, could stop this process, accelerate it, or delay it.

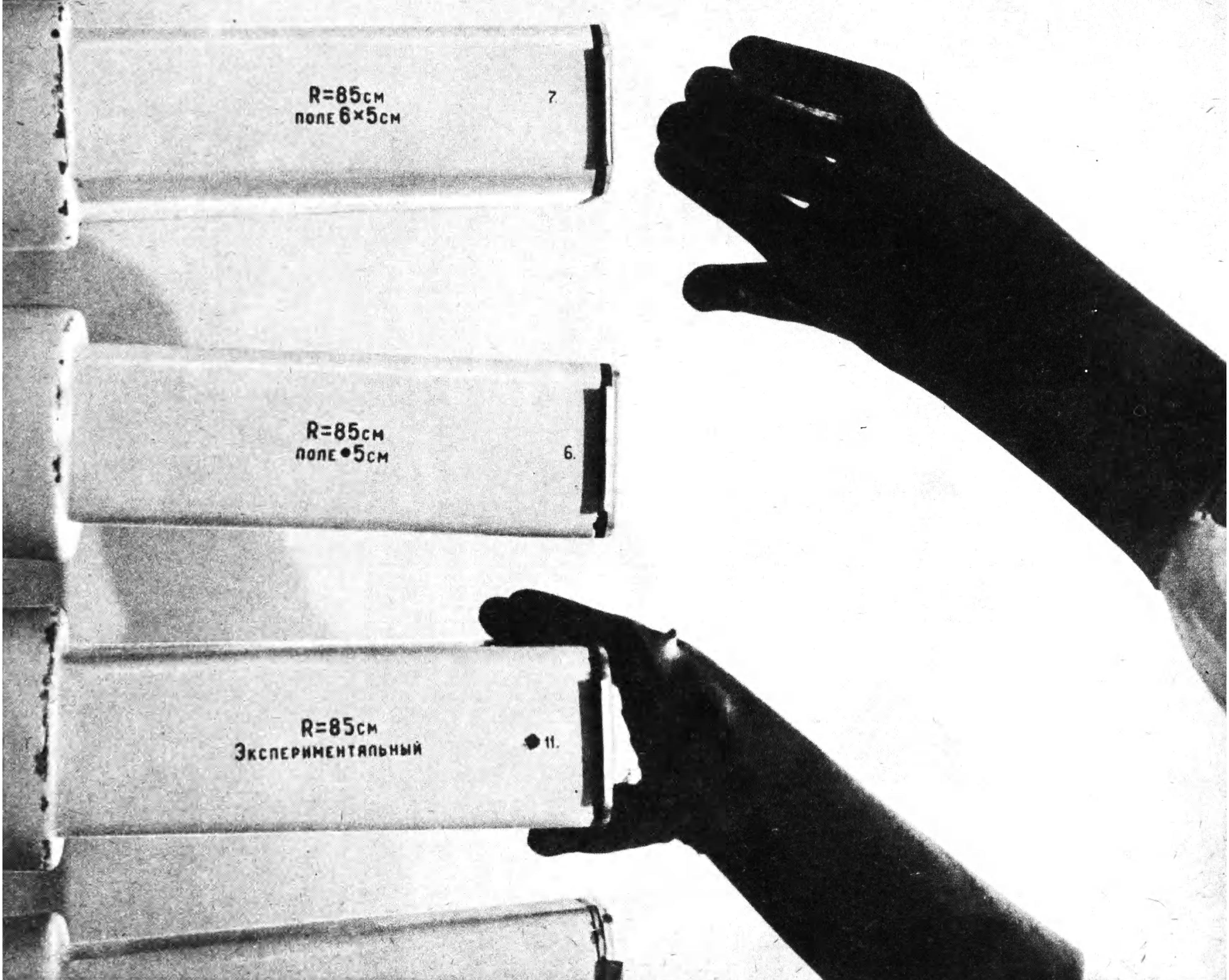
Almost 'Perpetual Motion'

Another property of radioactive substances, which we have already mentioned, proved no less striking. Their spontaneous decay is accompanied with the liberation of vast amounts of energy exceeding the energy involved in the most powerful chemical reactions known by hundreds of thousand times.

We already know that one gram of radium can yield around 136 calories of heat an hour. When, after several thousand years, all its atoms have completely disintegrated, the energy released will be 2 800 000 large calories, an amount equivalent to the heat obtained from burning around 375 kilograms of the best coal.

The sole difference is that the power from burning coal can be released in a comparatively short time while it would take several millenia to obtain the full energy from the decay of a gram of radium.

But what if we succeeded in producing an ingot weighing a ton? Such a lump of radium would liberate 136 million calories of heat an hour, an amount sufficient to create a practically eternal engine or perpetuum mobile of the order of several hundred horse power.


R=85см
поле 6×5см
7.
R=85см
поле ●5см
6.
R=85см
Экспериментальный
●11.

Chapter Three

ANOTHER RIDDLE OF NATURE

The Great Emptiness

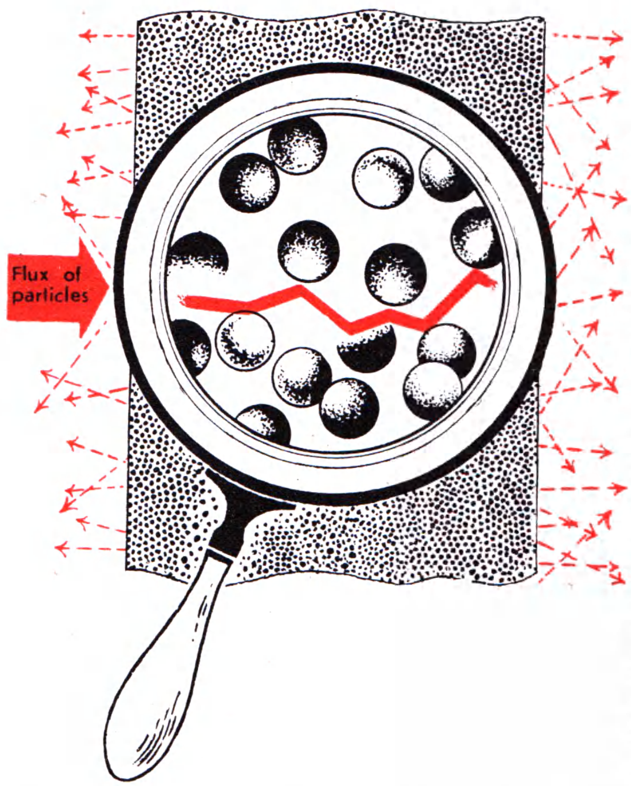
The discovery of radioactivity revealed to scientists that the atoms of certain substances continuously emitted material particles, atoms of helium and electrons, and that electrical charges, positive and negative, were connected with these particles. Much was still obscure in the phenomenon of radioactivity itself but scientists had already grasped what a valuable means it would be for investigating the structure of the atom.

So, arming himself with this new, powerful tool, Rutherford occupied himself over the years 1903-12 with studying the structure of the atoms of various substances bombarding them with particles emitted by radioactive elements. The essence of his experiments was as follows. A very thin sheet of gold foil was put in the path of a narrow beam of alpha-particles from a radioactive substance, and the alpha-particles registered on a luminescent screen (zinc sulphide) placed around the target.

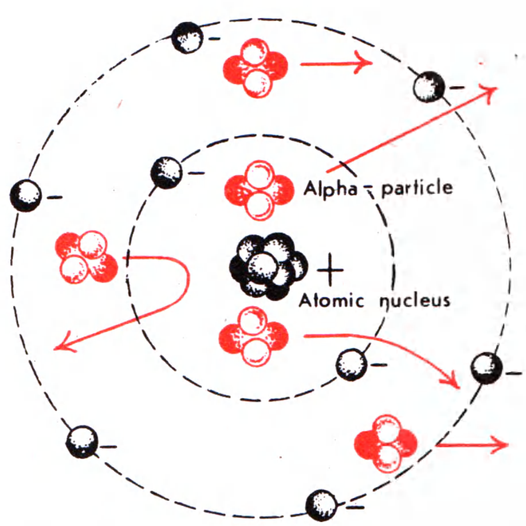
What would happen when the alpha-particles struck atoms of gold if the latter were solid spheres? Would they push the atoms aside, forcing their way through them? Or would they recoil in a different direction?

If the alpha-particles had to force their way somehow through the atoms of gold they would naturally collide with a host of them and change direction hundreds and thousands of times. And as a result they would be scattered, that is they would fly off from the gold foil in all directions.

That is not quite what happened. Most of the alpha-particles passed through the metal with almost no deviation from the straight path, and only a few were deflected at large angles, or even occasionally repelled backwards.



This is the scatter that would be expected if alpha-particles were used to bombard elements consisting of solid spheres



This is the way alpha-particles are scattered in fact by atoms

In fact, the only probable explanation of this phenomenon was that positively charged alpha-particles encountered other, still stronger positively charged particles in their path, whose charge and mass were so large that the alpha-particles were scattered in all directions and even backward, notwithstanding their enormous speed (around 20 000 kilometres per second) and, consequently, enormous energy.

But such enormous repulsive forces could not be possessed by atoms, whose positive charges, as Thomson supposed, were evenly distributed over the entire sphere.

But quite a different picture was obtained if it was supposed that the whole positive charge and mass of an atom were concentrated in a very small volume. Then, the two positive charges of the approaching alpha-particle would be opposed by the force of the like charges of the atoms of gold concentrated, as it were, into a fist. Being unable to overcome such a powerful obstacle, despite its speed, the alpha-particle would be forced aside or, in the event of a direct hit, would rebound backwards.

Two year's painstaking bombardment of all the 'nooks and crannies' of the atom finally confirmed the second assumption and made it possible to detect the positively charged part of the atom, its nucleus, in which almost its whole mass was concentrated. The nucleus occupied only a very small part of the total volume of the atom, about one hundred thousandth of its cross section.

The atoms had turned out to be empty!

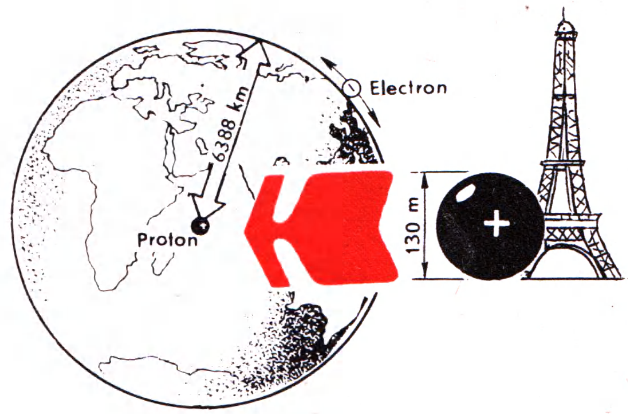
Imagine an atom the size of the Earth. Then its electrons, located on the extreme boundary of the atom would form a kind of shell of footballs rolling over the surface of the Earth, while the positively charged atomic nucleus

would be a ball only about 130 metres in diameter, located at the very centre. They would be separated by an empty space 6378 kilometres wide.

On the other hand, if we were to imagine a substance whose atomic nuclei were in close contact with one another, one cubic centimetre of it would weigh 114 million tons.

Since sooner or later we shall have to answer another very intriguing question, we might as well pose it now and try to answer it in several ways: what is it that prevents atoms from coming close together and forming this nuclear substance?

In the first place the negative charges of the electrons would prevent its formation; they repulse one another with a force such that it is impossible for atoms to approach each other closely enough. But if the atoms lost their first line of defence, the electron charges, their positively charged nuclei would repulse one another with even greater force. We have already learned how easily the nucleus of an atom of gold repulsed an approaching alpha-particle, just like a rubber ball, although the particle was travelling at the enormous velocity of 20 000 kilometres per second.



Why the atom can be considered empty

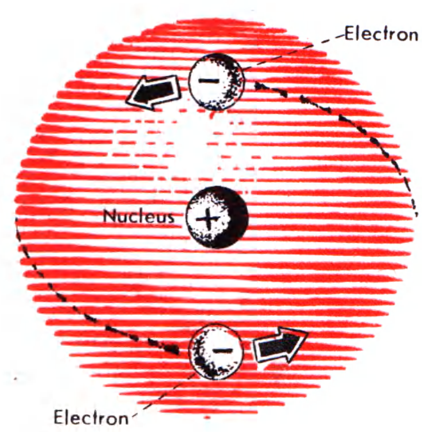
How is the Atom Constructed?

In the experiment described above, this theory explained how the alpha-particles flying past the positively charged nucleus of an atom of gold would move, how far they would be deflected from it, and at what points they would hit the luminescent screen.

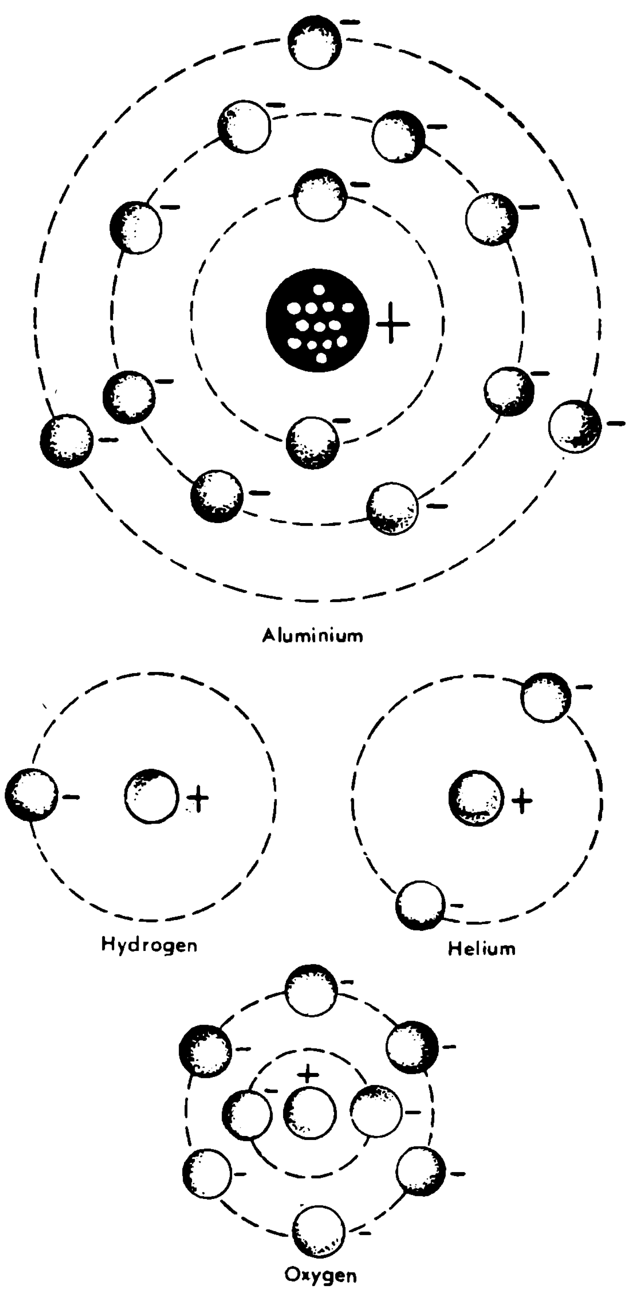
Rutherford's experiments, carried out with immaculate accuracy, made it possible to construct a new, 'planetary' model of atomic structure. According to this model the atom consisted of a positively charged nucleus located at its centre with electrons rotating around it, forming a kind of outer shell. It was called 'planetary' by analogy with the solar system, since the electrons rotated around the nucleus like the planets around the Sun.

The chemical properties of elements depend on the number of these rotating electrons, and on their arrangement in the atomic shell.

Rutherford's ideas were further developed by his pupil, the famous Danish scientist Niels Bohr; and properly speak-



The model of an atom proposed by Rutherford and Bohr



Planetary models of the atoms of hydrogen, helium, oxygen, and aluminium

ing this model of the atom should be called the Rutherford-Bohr model.

The simplest atom is that of hydrogen. Its nucleus, known as a proton, is 1836 times as heavy as the single electron rotating around it, spinning, in addition, around its own axis.

The atomic nuclei of all other elements are heavier than the proton. For instance, the mass of the nucleus of the next element in the Periodic Table, helium, is four times that of the proton. It has two electrons rotating around it. The nucleus of uranium is 238 times heavier than the proton, and has 92 electrons rotating around it.

The number of electrons in orbit around the nucleus of an atom is always equal to the positive charge of the nucleus, which explains why the atom as a whole is neutral; and the number of electrons coincides precisely with the atomic number of the element.

Mendeleev was right when he did not arrange certain elements in order of increasing atomic weight (which could not be measured accurately for reasons that will be clear to the reader a few pages further on). The chemical properties of these elements depend exclusively on the number of electrons in the outer shell of the atom, which has proved to be more important than their atomic weight.

Another of Rutherford's pupils, the Englishman James Chadwick, tried to calculate the charge of the atomic nuclei of copper and silver, based on the scattering of alpha-particles. The atomic number of silver in Mendeleev's Table is 47; the number obtained by Chadwick was 46.3 ± 0.7. For copper, in the 29th box in the Periodic Table, experiments gave 29.3 ± 0.45 (the plus and minus signs signify the possible error there may have been in the measurements). That, of course, was excellent agreement between theory and experiment.

In 1913 the Polish scientist Kasimir Fajans and the Englishman Frederick Soddy established very exactly how radioactive disintegration occurred. The rule they formulated is known as the Fajans-Soddy displacement rule.

When the atomic nucleus of a radioactive element emits an alpha-particle, it loses two units of positive charge and four units of mass. The lighter element so formed occupies a position in the Periodic System two places to the left of the initial or parent element.

With beta-decay the mass of the atomic nucleus remains practically unchanged, but its positive charge increases by one unit, since it emits a negative particle. Having emitted an electron, the atom moves one place to the right of the parent in the Periodic Table.

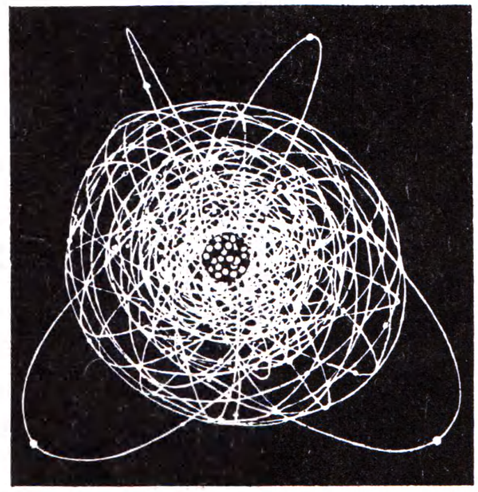
Thus, the nucleus of an atom of radium, for instance (atomic number 88, atomic weight 226), having emitted an alpha-particle, is transformed, as said above, into radon (atomic number 86, atomic weight 222).

The beta-emitter radium B (atomic number 82, atomic weight 214) turns into radium C (atomic number 83, atomic weight 214) after losing an electron.

Radioactive disintegration and the various reactions that atomic nuclei undergo can be expressed by formulae, like those of chemical reactions. The atomic weight of an element is written above and to the right of the symbol, and the atomic number below and to the left. Thus the radioactive decay of radium can be expressed as follows:

$$_{88}Ra^{226} \rightarrow {}_{86}Rn^{222} \rightarrow + {}_{2}He^{4}$$

Here $_{88}Ra^{226}$ is radium (atomic weight 226; nuclear charge 88); $_{86}Rn^{222}$ is radon (atomic weight 222; nuclear charge 86); and $_{2}He^{4}$ (an alpha-particle) is a nucleus of helium (atomic weight 4, nuclear charge 2).

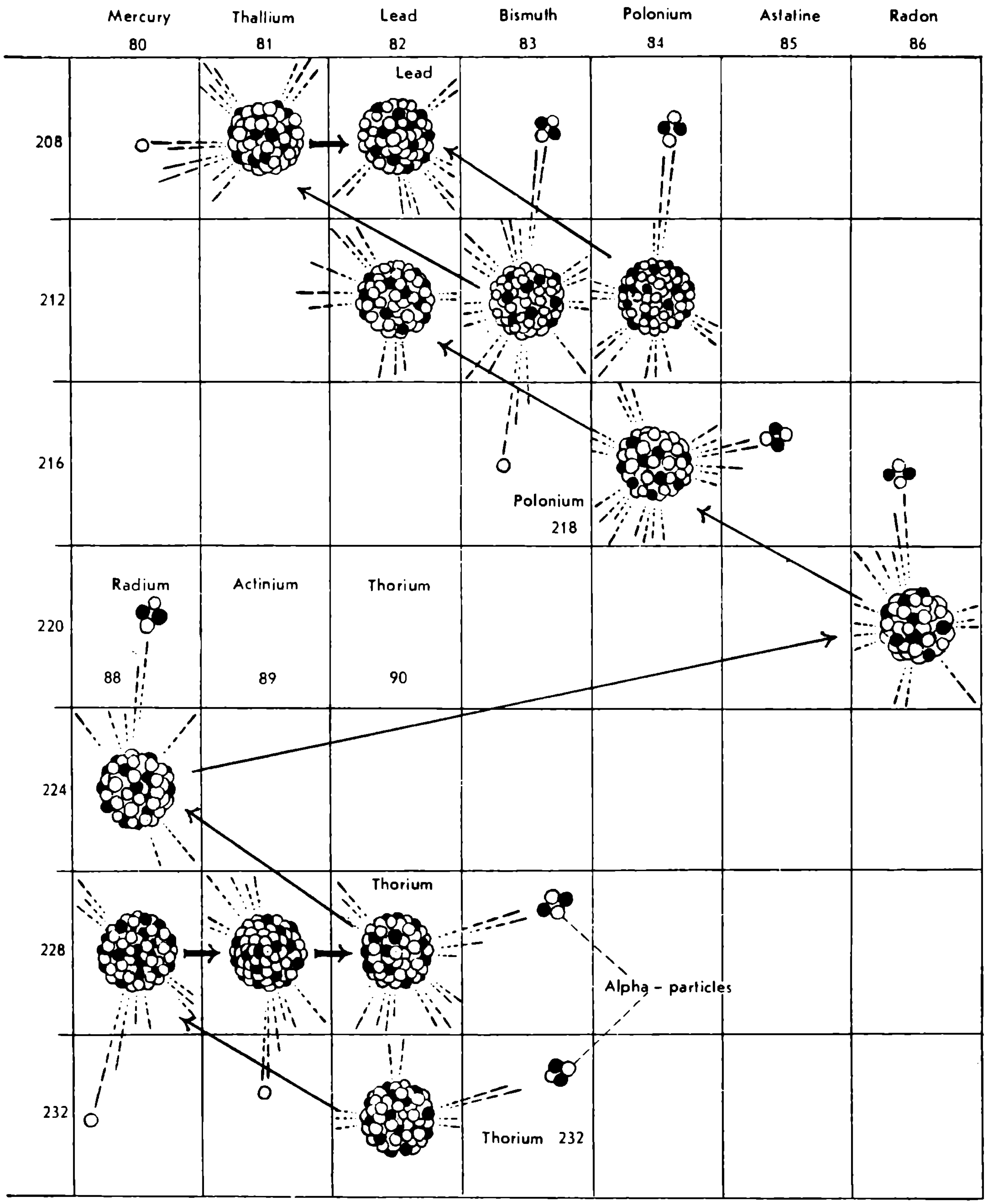


The uranium atom

This is the way we shall show radioactive disintegration in the rest of the book.

What is Meant By 'Energy Level' and 'Electron-Volt'?

The planetary model of atomic structure very approximately and quite inexactly describes the purely external, speculative picture of the mutual arrangement of the nucleus and the electrons revolving around it. And later on, the analogy of the solar system will be found very arbitrary and of limited value since the behaviour and interaction of the particles of which an atom is composed do not obey laws that can be grasped by ordinary human common sense. In short, it will be much easier to describe and understand the behaviour of electrons and their interaction with the nucleus and the atom as a whole if we skip the concepts of shells, orbits, rotation trajectories, velocities, etc., and pass



How nuclear charge and mass are altered by radioactive disintegration, in accordance with the Fajans-Soddy displacement rule

directly to the concept of energy levels, although, in order to simplify our description, we shall continue to use these terms quite often.

For each place in space occupied by an electron spinning about its own axis and rotating around the atomic nucleus at a certain distance from it there corresponds a strictly determined energy level; and an electron can only be at any particular level if the amount of energy separating it from the energy level of another electron (and consequently also its distance from the nucleus) is exactly equal to a definite value. The further a rotating electron is from the nucleus, the higher its energy level will be. Not more than two electrons can occupy any one energy level in an atom.

When, in the infinitely remote past of the Universe, atoms were first formed, not every combination of nuclei and electrons at once produced a complete atom of some particular element. On the contrary, atoms became as we now know them, only when, after many failures, a strictly defined number of electrons had been finally forced into their shells.

On Earth we find them ready-made and it does not occur to us that they could once have been quite different.

Thus for any atom of a given chemical element there are several stable (or stationary) states, in each of which its electron shell has a quite definite energy content or level. When an atom is in one of its steady states, it emits no energy, for that is only possible when an electron returns from an orbit corresponding to an excited state of the atom to an orbit corresponding to its normal, or ground, stable state. Therefore, energy is radiated only when an atom passes from one stationary state to another state, possessing a lower energy level. The energy emitted then is exactly equal to the difference between the initial and final energy levels. We shall talk about this in greater detail in Chapter IV.

The energy of atomic particles is infinitesimally small, no matter how fast they move, and cannot be measured by ordinary quantities. Even the smallest unit of energy, the erg*, is not suitable. (When you pick up a book weighing 900 grams and put it on a shelf you increase the energy of the atoms of which it consists by 25 million ergs.)

Therefore, a special unit was adopted for measuring the energy of these particles. It is known as the electron-volt (abbreviated eV).

What is an electron-volt?

When a charged particle enters an electric field, it is accelerated to a high velocity and its energy, of course, is increased at the same time. The new unit of energy, the electron-volt, is equal to the increase in the energy of an electron accelerated in a field of one volt (V).

In an electric field with a potential difference of one volt an electron acquires a velocity of 593 kilometres per second and a kinetic energy equal to the product of its charge and the potential difference, i.e. to 1.6×10^{-12} erg, or $1.6\times\times10^{-19}$ joule**. This energy we call one electron-volt. The average kinetic energy of molecules in random motion and of the atoms of a gas at room temperature (20°C) amounts to about 0.03 eV. Careful measurements of the energy levels of particles on the surface of the Sun (whose temperature is about 6 000°C)

* An erg is the work done by a force of one dyne acting through a distance of one centimetre. A dyne, in turn, is the force which, acting upon a mass of one gram, will give it an acceleration of one centimetre per second per second.

** The joule, the practical unit of work, equals 10^7 ergs.

have given an average energy of thermal motion of particles in the solar atmosphere around 0.5 eV. An energy of 1 eV corresponds to a temperature of 11 600°C.

An Inquisitive Doctor

Since scientists first succeeded in determining the atomic weights of various elements, albeit approximately, they have always been struck by the regularity with which atomic weight increases from element to element. When the weight of the lightest element, hydrogen, is taken as unity, the atomic weights of all the other elements are almost exactly expressed by whole numbers.

This amazing regularity gave occasion, as early as 1816, for the London physician William Prout to ask why, if the atoms of all chemical elements were the primary basic particles, genuine 'bricks of the Universe' that could not be decomposed into particles and were not bound at all to each other, the atom of nitrogen was exactly 14 times, and the atom of oxygen 16 times, as heavy as the hydrogen atom.

In Prout's opinion the atoms of all substances were built up from atoms of hydrogen. The nitrogen atom consisted of 14 hydrogen atoms, the atom of oxygen of 16 hydrogen atoms, and so on.

This idea could have had great influence on the development of chemistry and physics if subsequent more accurate measurements of atomic weights had not shown that atomic weights were not multiples of the hydrogen atom, and that the difference was occasionally so great that it could not be attributed to errors of measurement, as it was in Prout's time.

No theory that satisfactorily explained the regularity noticed by Prout was suggested at that time, and this brilliant conjecture by a physician with a questing mind sank into oblivion, to be revived again, this time with greater success and in new and greatly modified form, at the beginning of the 20th century.

Rutherford had shown that the nuclei of all atoms were positively charged, and that the mass of the nucleus is practically that of the whole atom.

But if one considers that the nuclei of all atoms consist of hydrogen nuclei or protons, then one point at once becomes unclear: the charge of the nucleus and atomic weight only coincide numerically for hydrogen. With all other elements the mass of the nucleus proves to be much greater.

But what particles, then, apart from protons, are components of the atomic nuclei? At first glance it would seem that the number of protons cannot be greater than the total positive charge of the nucleus. Or are the protons of each atom, perhaps, different?

To overcome this obstacle, a new model of atomic structure was proposed and substantiated, taking into account what we have just spoken about.

Let us see what it was.

The nuclei of all atoms, it said, were built up of protons whose number was exactly equal to the atomic weight of the element. But apart from the protons, the nucleus incorporated electrons whose negative charges neutralized a fraction of these positively charged particles. The number of these electrons was equal to the difference between the atomic weight of the nucleus and its total charge.

That quite positively explained all the facts then known, and beta-decay served as evidence of the presence of electrons in the nuclei, since very real electrons escaped then from the atomic nuclei of radioactive substances.

Some scientists even assumed that, in addition to protons and electrons, heavy nuclei might also contain alpha-particles.

What is an Isotope?

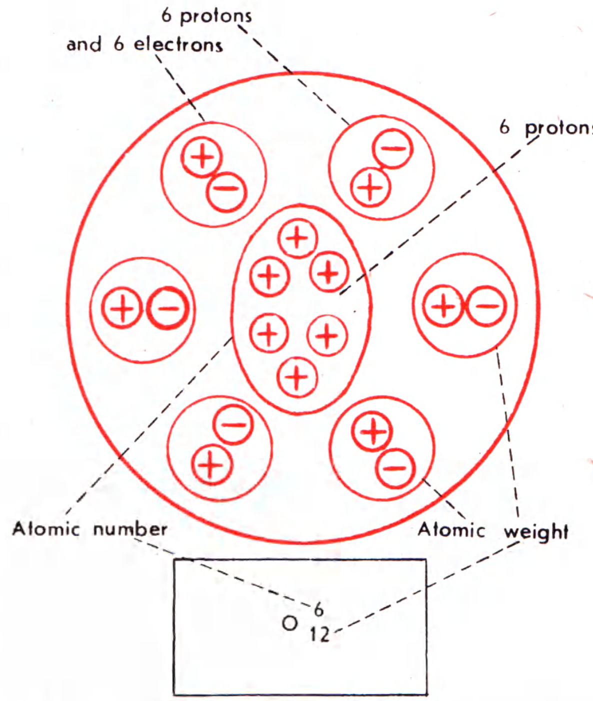
But the circumstances mentioned above still prevented full acceptance of the proton-electron model as a picture of nuclear structure.

It was a question of the inexplicable contradiction already mentioned between the atomic number of an element (i.e. the whole number of the positive and negative charges of atom, which determined its chemical properties) and its fractional atomic weight, now exactly established.

If it is taken that the lightest of all atoms, that of hydrogen, consists of one proton and one electron moving around it, this atom, as Prout had quite convincingly shown in his time, could undoubtedly be the elementary brick from which all the other, more complicated atoms are built up.

The atomic weight of any element was originally determined as its weight in relation to that of an atom of hydrogen. Later the atomic weight of an element was assumed to be equal to the ratio of the weight of its atom not to the weight of an atom of hydrogen, but to one-sixteenth of the weight of an atom of oxygen, which is 1.674×10^{-24} gram. This weight was given the name of the *atomic mass unit* (amu). It should be noted, however, that scientists decided some years ago to take the atomic mass unit as the weight of one-twelfth of the atom of carbon, $_6C^{12}$.

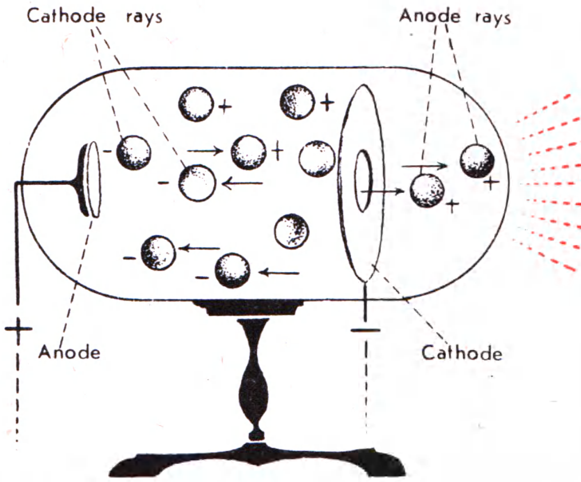
If Prout had been right the weight of an atom of oxygen and the weight of 16 atoms of hydrogen would be identical. But there is another difficulty: the atomic weights of all other atoms are not equal to the sums of the weights of their component hydrogen atoms, but for some reason or other acquire fractional values. The atomic weight of iron, for example, is 55.75; and even though it could still be assumed that the iron



This is how scientists envisaged the structure of the atomic nucleus in an effort to explain the inconprehensible difference between its atomic number (charge) and atomic weight (mass)

atom is that much heavier than an atom of hydrogen, even the most imaginative of us would not envisage it as composed of 55 hydrogen nuclei plus 75/100 of another one.

In the course of their investigations of radioactive elements scientists came across some other incomprehensible phenomena. The chemical properties of many of the newly discovered radioactive substances proved to be similar to those of elements already known. For instance, the element ionium $_{90}Io^{230}$, discovered in 1906, proved to be identical with the well-known element thorium, and it was impossible to separate them by any of the chemical methods then available. Mesothorium, discovered the following year, did not differ chemically from radium. The lead obtained through full disintegration of radium had all the properties of ordinary lead but



Schematic diagram of the tube by means of which cathode rays and so-called canal rays (a flux of positively charged ions) were first obtained

differed from it in atomic weight. And so on.

Thus certain places in Mendeleev's Table were filled by several kinds of atom of equal charge but different mass. These atoms were given the name 'isotope' (from Greek *iso* the same and *topos* place).

Mesothorium-1 turned out to be an isotope of radium, ionium of thorium, radium B and radium D of lead.

It proved, however, that radioactive substances were not alone in having isotopes. By means of special devices and intricate instruments and apparatus scientists succeeded in showing that all existing elements had isotopes.

How did they manage that? How did they succeed in showing that there were identical elements with different atomic weights? To do so it was necessary, surely, to separate these atoms from one another. But how? It could not be done chemically since they were completely identical in their chemical properties. An electric field was also of no use since the number of electrons and the nuclear charges of the isotopes were also identical.

An Atom-Sorting Machine

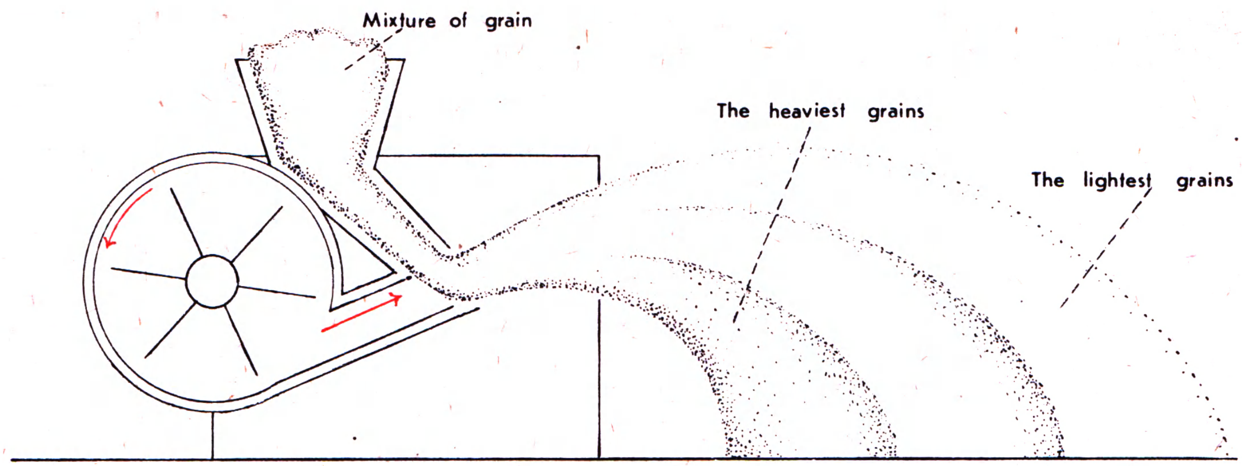
To separate atoms that were so closely alike special machines were conceived. As we have already said, the atom is neutral in its ordinary, ground state. For an electric or magnetic field to be able to affect it, it must be given an electric charge, or ionized, by detaching one or more electrons from it. Then it will be converted into a positively charged ion on which an electric or magnetic field can act.

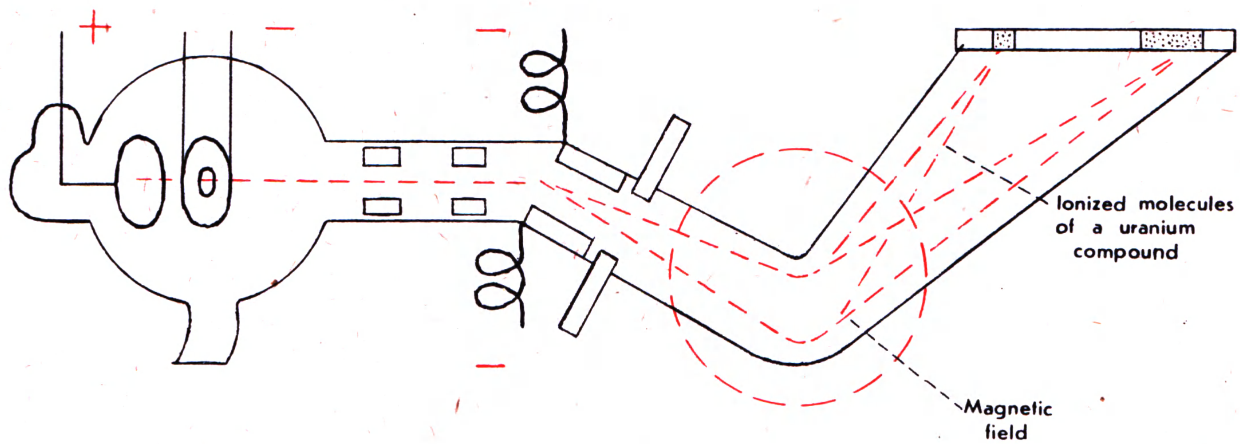
For that purpose the element that interests us must be converted into the gaseous state and put into the instrument (tube) shown in the sketch on p. 36.

For several reasons any gas always has a certain number of free electrons. If a sufficiently high voltage is applied to the electrodes of the instrument, these free electrons will immediately stream to the positively charged anode, and in colliding on their way with the remaining atoms of the gas will ionize them. The new free electrons so formed will in turn be attracted to the anode and on their way will detach electrons from any atoms encountered, and so on. The number of ionized atoms will multiply like an avalanche.

But what will happen to the positively charged ions of gas being formed in the chamber? They will be attracted in the opposite direction, to the negatively charged electrode, or cathode, of the tube, also at very high speed, but rather slower than the electrons.

The cathode has an opening in the form of a long, narrow passage. Not all the ions flying to the cathode will enter the opening, but some will, those that are moving along its axis. Being accelerated by the negative voltage applied to the cathode ions entering the opening will fly along the passage and pop into the second, elongated part of the tube. There, by means of electrodes to which





The mass-spectrograph, an instrument by which isotopes are sorted

a high negative voltage is applied, they are further accelerated and fly through a strong magnetic field, the effect of which is to bend their path so that they hit a special plate or target.

Ions with different masses, of course, will be deflected by different angles by the magnetic field. The lighter an isotope is the more its trajectory will be bent in the magnetic field. As a result the various isotopes, having passed through the magnetic field, will each be concentrated on a definite part of the target.

By repeating this operation several times an element can be almost completely separated into its constituent isotopes.

A quite complicated instrument for separating isotopes, the Aston mass spectrograph, works on this principle. It is called after the British physicist who designed it. By means of instruments like it scientists have investigated all the elements of Mendeleev's Periodic Table. It has been found that some have a small number of isotopes and others dozens of them.

It was now very simple to answer the riddle that had so puzzled scientists, that is to say, the fractional atomic weights of certain elements.

The fact is that the isotopic composition of every element occurring on Earth is constant. And since an element consists of atoms differing in mass their common atomic weight may well be fractional. Let us consider, for example, the gas neon. Its atomic weight is 20.2. Exact measurements have shown that it is actually a mixture of three isotopes, 90 per cent consisting of one with an atomic weight of 20, 0.27 per cent of another with an atomic weight of 21, and 9.73 per cent of a third with an atomic weight of 22.

Now let us calculate the atomic weight of the complete mixture of the natural element neon:

$$20 \times 0.9 + 21 \times 0.0027 + 22 \times 0.0973 = \\ = 20.1973 = 20.2$$

The atomic weight of neon obtained experimentally is 20.2. So, as you see, the two results completely coincide.

Natural iron consists of four isotopes with atomic weights of 54, 56, 57, and 58; in the mixture of this element they give an atomic weight of 55.84.

Even some of the elements like hydrogen and oxygen whose atomic weights are measured, in practice, in whole numbers, also proved to consist of several isotopes. Thus, oxygen was found to have three isotopes. The main one (99.76 per cent) had an atomic weight of 16; the other two had atomic weights of 18 (0.2 per cent) and 19 (0.04 per cent) respectively.

So that is the way the puzzle was solved.

The World of Minute Particles and Enormous Energies

In spite of the disgressions, voluntary and unintentional, that we have had to make in the preceding chapters, we are still interested in the main question of our whole story, that is, why do all these various physical effects and chemical reactions not influence the nucleus of the atom.

The answer is that ordinary forces and energies can only bring atoms together until their electron shells come into contact and begin to react with one another.

As for nuclei, they are so infinitesimal that they are still enormous distances apart from each other and from the points of contact of their electron shells. A reaction between them in the course of which the nuclei themselves were changed could only be produced if we could force them into contact. But such contact, as we have seen, is prevented by their positive charges. The forces of repulsion acting between them, according to Coulomb's law, are directly proportional to their charges and inversely proportional to the square of the distance between their centres.

At first glance the forces of repulsion acting between the infinitesimal volumes and masses of atomic nuclei would seem to be quite insignificant. But that is not so. The repulsion of electrically charged bodies separated by distances comparable to those between atomic nuclei is incredibly great.

Nevertheless, scientists posed the problem of whether it was possible to penetrate the nucleus of the atom, and not just to penetrate it but to try and disturb its structure, and perhaps even smash it, so as to learn what it was and from what it was built.

'Atomic Artillery'

If that could be done, it might enable man to achieve his ancient dream of transforming elements. Scientists hoped to achieve this aim by means of 'atomic artillery', that is to say, the particles emitted by radioactive elements.

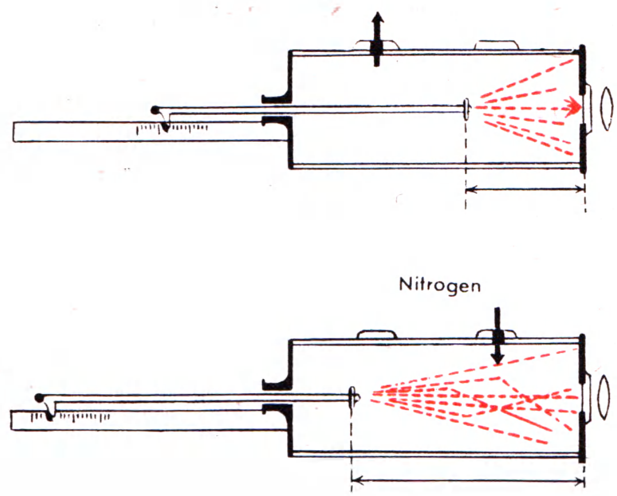
Only these particles, or particles accelerated in the special accelerators that were developed at that time, could penetrate to the nucleus, smash it, or disturb the structure of this rather strong body. A new nucleus might be formed in this way, or the nucleus might be broken down into its constituent particles.

The scientists, of course, were well aware of the difficulties facing them.

It was already known that the atomic nucleus was protected by a kind of double armour. It was protected against intruding electrons by the strength of its powerful electron shell and it was reliably defended against positive ions by the repulsive force of its own total positive charge.

As with ordinary artillery the governing factors with 'atomic artillery' are the velocity and weight of the projectile. The electrons emitted by radioactive substances move with enormous velocities but their mass is so small that they are easily deflected from a straight path. Alpha-particles, in turn, while much heavier than electrons (over 7 000 times as much), travel with a velocity around 15 times slower. The chances of alpha-particles reaching the nucleus are therefore greater, in general, than those of electrons, but to get through to the nucleus of heavy elements, they must have an energy of at least 25 MeV, whereas the energy of the fastest alpha-particles emitted by natural radioactivity does not exceed 10.6 MeV.

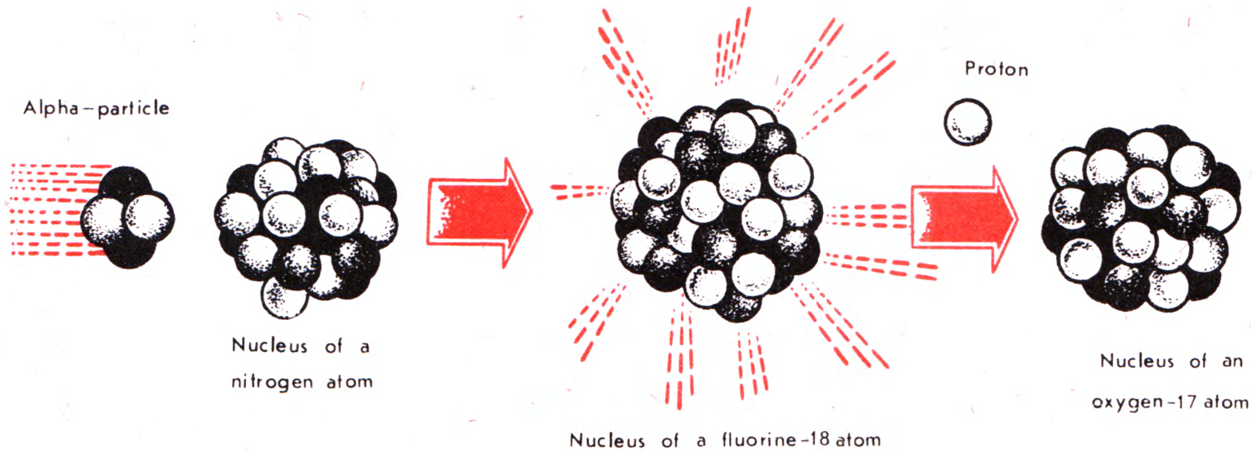
It was therefore clear from the very beginning that it would be futile to try and bombard the nuclei of heavy elements with alpha-particles. The only approach that could be expected to yield results would be to bombard the nuclei of the lightest elements and try and score direct hits. But even that was like trying to shoot sparrows with a cannon. The only inexactitude in our comparison is that it would be more rewarding and give better results to shoot sparrows with cannon, because the target would be bigger and the number of hits would certainly be greater.



This is how the first atomic gun looked, used in Rutherford's experiments

Yet it was with the most optimistic expectations and more than modest resources that Rutherford began in 1919 to bombard the atoms of a number of the stable elements with alpha-particles, in an effort artificially to induce their transmutation into other elements. His amazingly ingenious and brilliantly conceived experiments were made with exceptionally simple means. A minute quantity of radioactive matter emitting alpha-particles was placed on a needle-point in the centre of a tube opposite an opening covered with thin metal foil. Behind the foil were a luminescent screen and a microscope for observing and counting the flashes occurring on the screen. The air was carefully evacuated from the tube and replaced by a gas.

The needle-point with the speck of radium was positioned in such a way that the alpha-particles emitted by the radium could not reach the screen. The idea behind the experiment was as follows.



This is the way scientists first succeeded in turning an atom of nitrogen into an atom of oxygen

If a heavy alpha-particle hit the nucleus of an atom of the gas filling the tube that nucleus would either be completely smashed or a fragment would be knocked off it. In either event the path of the lighter fragments of the smashed atom would be much longer than that of the bombarding alpha-particles and would reach the screen and cause it to fluoresce (scintillate).

For a long time the experiments yielded no results, until the tube was filled with nitrogen. Then individual bright flashes appeared on the luminescent screen, that is to say, traces of particles knocked off the atoms of nitrogen.

When the velocity, path length, and mass of the particles were calculated, they proved to be protons, that is, nuclei of atoms of hydrogen, which had obviously not been in the tube.

It remained only to suppose that after a direct hit on an atom of nitrogen, the alpha-particle did not rebound but stuck to it in some way so that a nucleus was formed with a charge of nine and an atomic weight of 18. This was the nucleus of an unstable isotope of fluorine, which disintegrated quite rapidly, ejecting a proton. The transmutation was accompanied by the formation of the nucleus of an isotope of oxygen with an atomic weight of 17. The transmutation of the nuclei can be written as follows:

$$_2He^4 + {}_7N^{14} \rightarrow {}_9F^{18} \rightarrow {}_8O^{17} + {}_1H^1$$

In combining with the nucleus of nitrogen the alpha-particle turned it into a nucleus of fluorine, which, on disintegrating, in turn, was transformed into a nucleus of oxygen and an individual proton.

This splitting of the atomic nucleus was the first artificial nuclear reaction in the history of science.

Carrying these experiments further scientists found that alpha-particles could be used to knock protons out of the nuclei of atoms of other light elements, transmuting them into the nuclei of heavier elements. Thus, for example, atoms of aluminium were transmuted into nuclei of silicon, by bombarding their nuclei with alpha-particles.

So, by bombarding the atoms of light elements with alpha-particles, man succeeded at last in transmuting one chemical element into another, though this was still a long way from producing real gold as they tried to do in the Middle Ages. But the importance of the discovery was far more important than simply a means of obtaining gold from lead.

Careful measurement of the energy of the protons emitted by the nucleus of fluorine-18 showed it to be much larger than that of the alpha-particles used in the bombardment, although the alpha-particles were four times as heavy; it seemed that the opposite should have happened.

If that were so, then there were grounds for considering that the nuclei of the atoms of ordinary elements as well as of radioactive ones were the potential source of unusual energy, which might, in favourable circumstances, be released.

In fact, the deeper scientists studied the atomic nucleus, the more grounds there were to compare it to a spring kept tightly wound up by unknown catches. They had still only succeeded in groping blindly and releasing a few of the catches.

As to the energy liberated by chemical and nuclear reactions, the following figures told the tale. Burning carbon liberated an energy of 4.2 eV per atom. To split a nucleus of aluminium and transmute it into a nucleus of silicon by means of an alpha-particle and a proton it was necessary to expend about 7.7 MeV of energy. But this reaction, together with the fragments, yielded 10.7 MeV, a net gain of 3 MeV, or 700 000 times as much as obtained from burning coal.

It would seem that this colossal gain of energy from the bombardment of atomic nuclei with alpha-particles had achieved man's objective. The breathtaking dream of a miraculous match box of inexhaustable energy came true.

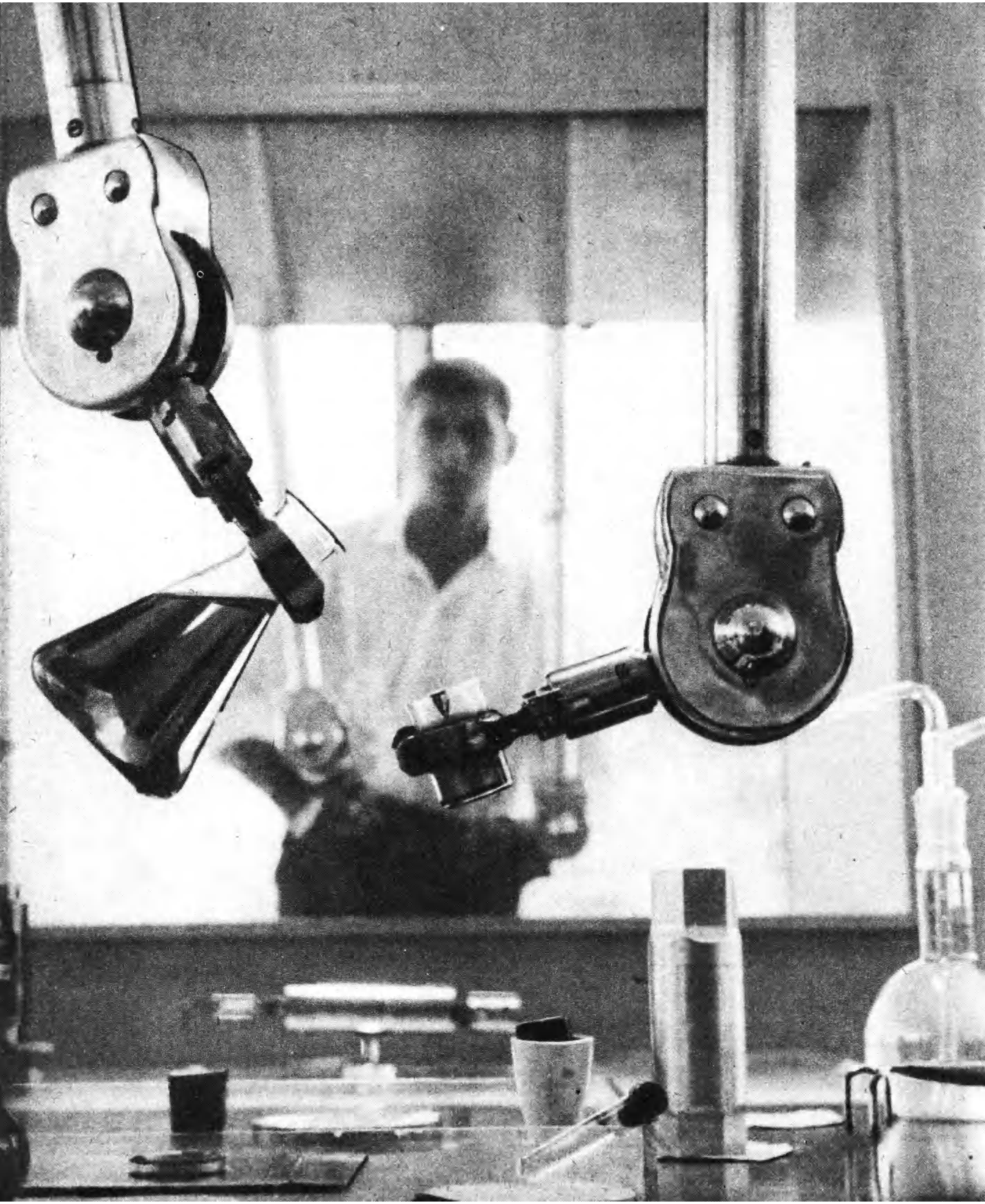
But only about 20 out of every million atomic 'shells' or alpha-particles fired at the nuclei of aluminium hit the target and split them with the appropriate gain of energy.

The remaining 999 980 alpha-particles flew past or were scattered. The results of the shooting were not comforting and were even discouraging—how galling to have reached the cherished goal and to be forced to lay down one's arms by the force of such irrefutable facts!

The facts clearly showed that the possible gain of energy from splitting 20 atoms did not compensate for even an insignificant fraction of the energy spent trying to 'shoot sparrows with a cannon'.

It was enough to drive one to despair.

But before we relate what came next in the exciting discoveries of scientists, let us acquaint ourselves with the basic methods of investigating nuclear particles. We have already spoken about the electroscope and spinthariscope. Now it is time to tell about more complicated instruments.



Chapter Four

THE SCIENTISTS' TOOLS

How They Managed to Count Atoms

Every field of science has its own means of research and its own delicate and precise instruments.

The astronomer's tools are the telescope, the camera, the spectrograph, very precise chronometers, and other instruments and apparatus; biologists and physiologists generally use the optical microscope, but now have the electron microscope; the chemist uses various chemical apparatus and an endless number of reagents, and so on.

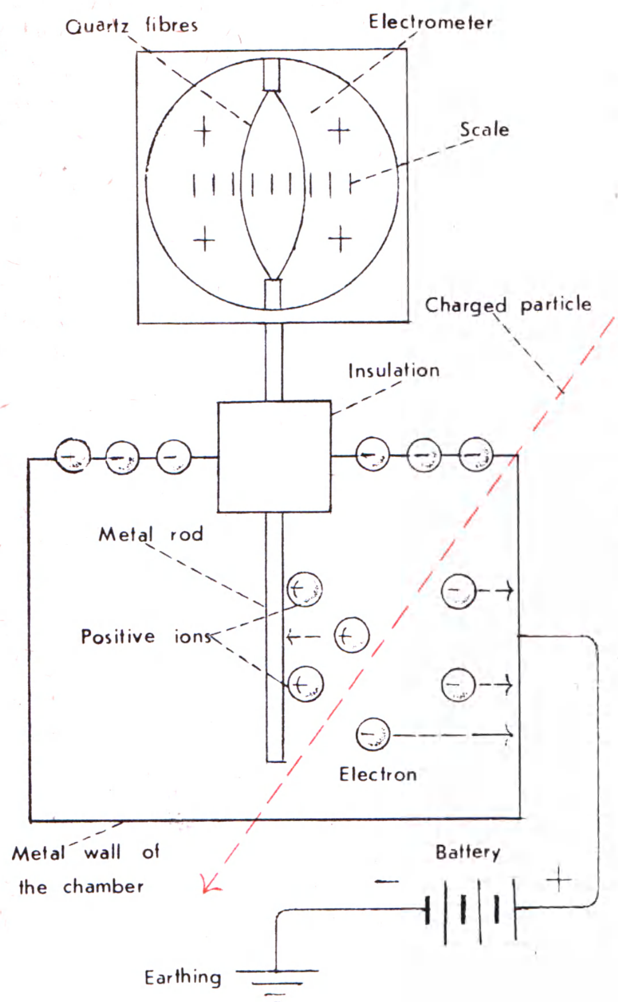
Most of the phenomena studied by atomic physicists cannot be directly observed; man's sense organs do not enable him to react to individual atoms and their constituent particles.

Therefore, in order to detect these particles we have to resort to various indirect methods based one way or another on phenomena of the ionization of matter by charged particles.

We have already said that if two oppositely charged electrodes are introduced into a vessel containing an ionized gas, positive ions will begin to flow toward the negative electrode and negative ions toward the positive electrode. The gas will become a conductor of electricity, and the electric current that flows through it can be detected by the most diverse means.

That is the principle that underlay the first and simplest instrument used in nuclear research, the ionization chamber, which is illustrated in the diagram above.

A charged particle passing through the chamber ionizes a certain number of atoms of the gas in it, and the ions formed are attracted by an electric field. The number of charges formed can be read off the scale of an electrometer connected to the chamber. The readings of the instrument indicate the number of particles passing through the cham-



The principle of the construction of an ionization chamber

ber. In spite of its simple construction, the instrument is hundreds of millions of times more sensitive than an analytical balance and a thousand times more so than spectral analysis.

But physicists need to know much more; they need to distinguish particles one from another, to be able to measure their energy and calculate their exact number, and to register the direction they are travelling in.

Taking into account the drawbacks of the ionization chamber, the German physicist Hans Geiger quite long ago suggested a rather different instrument for detecting charged particles. Later he improved it in co-operation with another physicist E. W. Müller.

The improved instrument is called a Geiger-Müller counter and consists of a metal tube with a fine metal wire stretched inside it, which usually serves as the positive electrode. A strong electric field is created between the wire and tube (500 or 800 volts, occasionally higher).

The tube is filled with dilute gas at a pressure of the order of 1/100th that of the atmosphere; and when a charged particle passes through it, it ionizes this gas. The electrons knocked out of the atoms of gas enter the strong electric field between the wire and the tube, are accelerated to high velocities, and begin themselves to ionize atoms of the gas with which they collide as they move toward the wire. The second-generation electrons, accelerated by the same field, also become capable of ionizing the gas, while electrons of the third generation in turn ionize new atoms, and so on. In short, the appearance of a single electron in the tube gives rise to a whole shower of electrons that rush toward the wire, i.e. brings about the flow of a brief electric current (pulse) between the electrodes; this current can easily be de-

tected by a measuring device, and, if necessary, can be amplified.

The sensitivity of the instrument is so high that it can be used, where necessary, to detect the appearance of a single electron or any other charged particle inside the tube. When it is fitted with a pulse counter it can also be used to count the number of particles passing through the tube per second, since each current pulse corresponds to one incoming particle.

Finally, if X-rays or gamma-rays pass through the tube, instead of charged particles, they too can be registered. On hitting the metal surface of the tube, gamma-rays knock electrons out of its atoms and when these electrons enter the electric field between the wire and tube, they too are accelerated and knock electrons out of the atoms of gas encountered, and so on. The instrument then functions in the same way as when charged particles enter it.

If several counters are connected in parallel in such a way that the pulse counter operates only when discharges occurring, say, in horizontal, vertical, or sloping tubes, coincide, the device can be used to determine the direction in which the charged particles are travelling.

A host of similar devices are available, designed to detect the most diverse particles and radiations. They are available in large sizes and small, stationary or portable, of low sensitivity for measuring intensive particle fluxes, or highly sensitive to detect single particles. Geiger-Müller counters are widely used in the most diverse branches of science and technology, and are probably the most common instrument for detecting invisible particles.

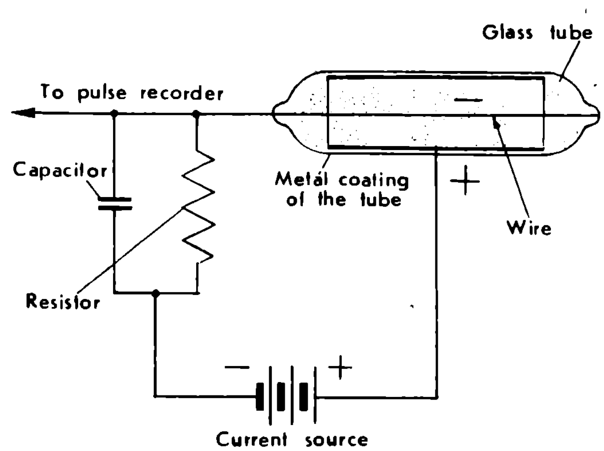


Diagram of the simplest Geiger-Müller ionization counter. It can even identify a single charged particle flying through it

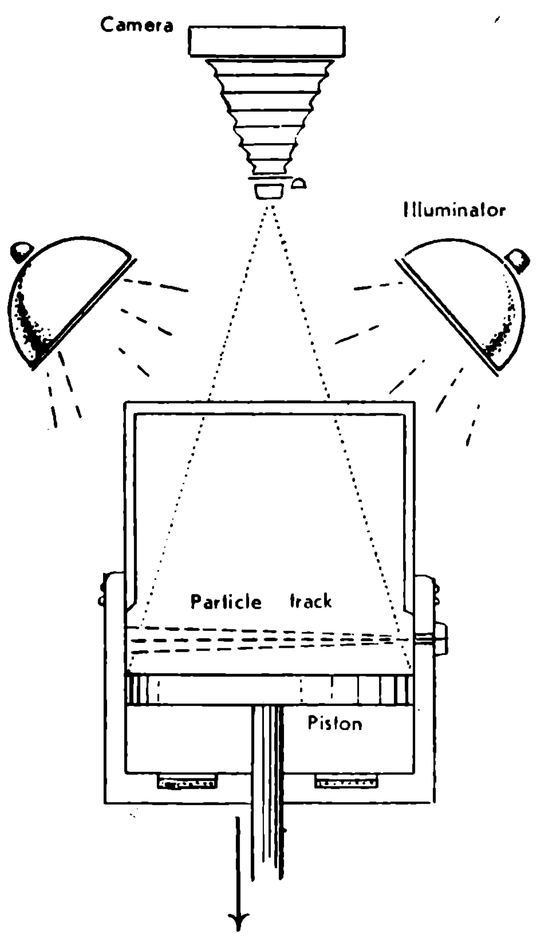
Fog That Makes the Invisible Visible

Usually, when something is not very visible, or when something blurs our sight, we say 'it's all a fog', or that 'everything is foggy'. But in certain circumstances, at least in the field of physics, fog makes it possible to see the invisible.

We know that air, no matter how dry and clear it is, always contains a certain amount of moisture continuously evaporated from seas, lakes, rivers, plants, and the soil.

A favourite question of particularly carping school examiners is: 'Can one see water vapour?'; and very frequently an absent-minded pupil hastily answers with an unfortunate 'Yes'. But water vapour is invisible; its separate molecules are distributed uniformly in the air and do not change its homogeneity, just as molecules of salt or sugar are invisible when dissolved in water.

But if the atmospheric pressure of air saturated with moisture drops sharply, the air becomes supersaturated, and then only is it possible to see vapour; individual molecules of moisture first unite into fine droplets, forming clouds, then into larger drops that, being unable to float freely in the air, fall as rain.



The Wilson cloud chamber

This phenomenon is linked with circumstances that are of great interest and importance in physical research: the excess moisture only begins to condense and collect into drops if there are small particles of dust or charged particles in the air, which explains why it is necessary to sprinkle clouds with fine sand or finely powdered chemicals in order to produce artificial rain.

In 1911 the English physicist Charles Wilson, who had previously done much research on the origin of rain and fog, proposed a very ingenious and amazingly simple instrument, a chamber for direct observation of the path of a charged particle.

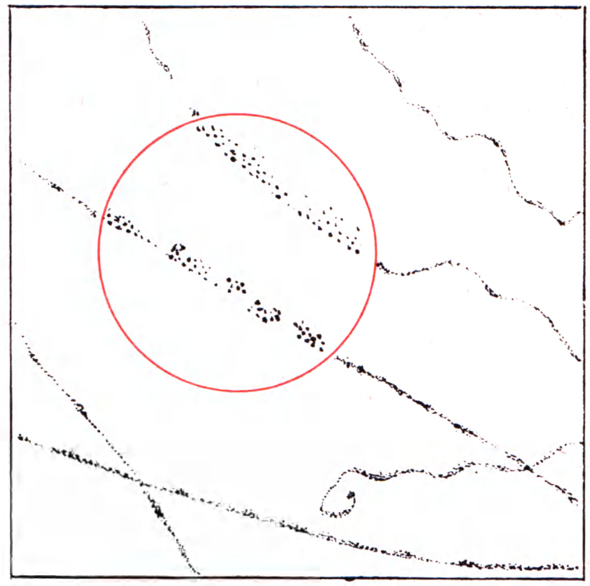
The Wilson cloud chamber consists of a glass cylinder with a moving piston instead of a fixed bottom. The cylinder is filled with air, saturated with the vapour of some liquid, like water or alcohol, or a mixture of the two. When the piston is pulled down very quickly, the pressure in the chamber drops abruptly and it becomes filled with supersaturated vapour. If it contains no dust or other suspended particles, it is difficult for the molecules of vapour to condense into drops and fog will not develop inside the chamber for a certain time.

But should a charged particle pass through the chamber at that moment, it would (as usual) ionize air molecules, which would immediately become centres of condensation. Its track would be instantly filled with a host of droplets and become visible as a thin but distinct line. These lines are particularly clear when they are strongly illuminated from the side and if the walls of the chamber and the piston are painted a dull black. At the end of an observation (visual or photographic) the piston must be returned to its initial position and an electric field created inside the chamber, so as to attract the ions of gas formed to the walls of the chamber. After a certain time has elapsed the instrument can be used again. This amazingly simple device not only makes it possible to see the tracks of flying particles, but also to determine some of their properties. From the thickness of the tracks, for instance, we can find whether the particle was slow or fast, and what charge it carried. The slower it moved, or the higher its charge, the more molecules it ionized on each centimetre of its path. If we photograph the tracks of particles whose velocity is known in advance, and the tracks of particles whose velocity is not known, then, by measuring the width and den-

sity of the tracks, we can determine quite accurately the velocity, and consequently also the energy, of the unknown particles we are studying.

From the length of a track, or rather from the number of droplets in it, provided it begins and ends inside the chamber, it is possible to determine the total number of ion pairs formed by the particle investigated. And knowing the energy expended in the formation of an ion pair, we can calculate the total energy the particle had when it entered the chamber.

Later, the Wilson cloud chamber was much improved; in particular, the piston was replaced by a thin rubber diaphragm that made it possible to use the chamber in any position. A particularly valuable contribution to its design was made in 1927 by the Soviet physicists P. L. Kapitza and D. V. Skobeltsyn who suggested placing it in a strong magnetic field. By interacting with the charged particles, the magnetic field deflects them from their straight path, and that first of all makes it possible to determine whether the particle's charge is positive or negative and, secondly, gives another way of determining its energy, since the faster a charged particle moves, or the larger its mass, the less it is deflected by a magnetic field.



Magnified picture of the track of a particle in a Wilson cloud chamber. The drops of moisture are distinctly visible

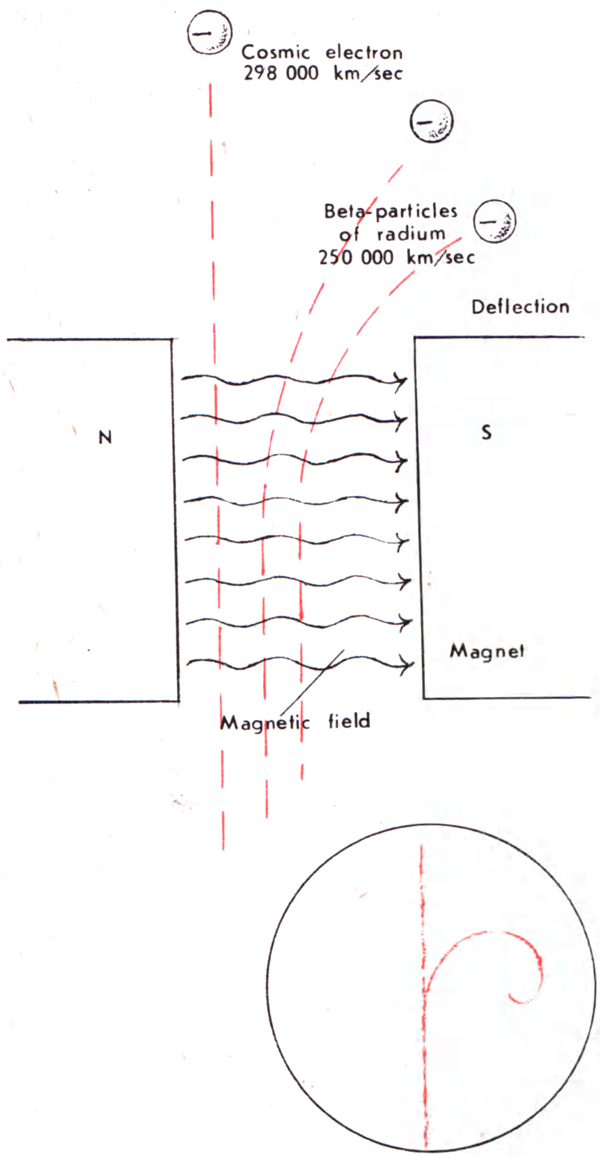
A Simpler Than Simple Instrument

However, even the Wilson cloud chamber, amazing in its simplicity and the exceptional accuracy and very convincing results it gave, had a number of serious shortcomings. Some were eliminated by making major alterations in its design but others required quite new, though rather similar, devices to be developed.

For instance, it takes at least five or ten seconds for the cloud chamber to become ready for a new observation after expansion. But during that time a very important nuclear event might be missed. Therefore, a chamber of rather different design was suggested in 1939, known as the diffusion chamber.

This chamber is a vessel containing either air or another gas which is kept at a high temperature at the top and cold at the bottom. A very volatile liquid (like alcohol) is evaporated in the upper part. Its vapour, being at relatively high pressure, diffuses continuously into the lower cold section where its pressure falls and it condenses in drops.

A sensitive zone seven to ten centimetres thick is formed somewhere between the two temperature extremes where the air is so supersaturated that as soon as a charged particle, or an ion, enters it, a track made up of very fine droplets of moisture is formed along the particle's track just as in the Wilson chamber immediately after expansion. But unlike the cloud chamber, the diffusion chamber remains sensitive to ionizing particles as



Particles passing through a magnetic field change their path in accordance with their charge, mass, and velocity. A slow particle moves in a circle, while a fast one is scarcely deflected

long as evaporation of the volatile liquid continues.

The frequency of observed particles in a diffusion chamber and of nuclear events like the collision of particles can be increased considerably if it is filled with gaseous hydrogen or helium under pressure (up to 35 atmospheres), and if a temperature difference of 100°C or more is maintained between the top (+30°C) and the bottom (—70°C).

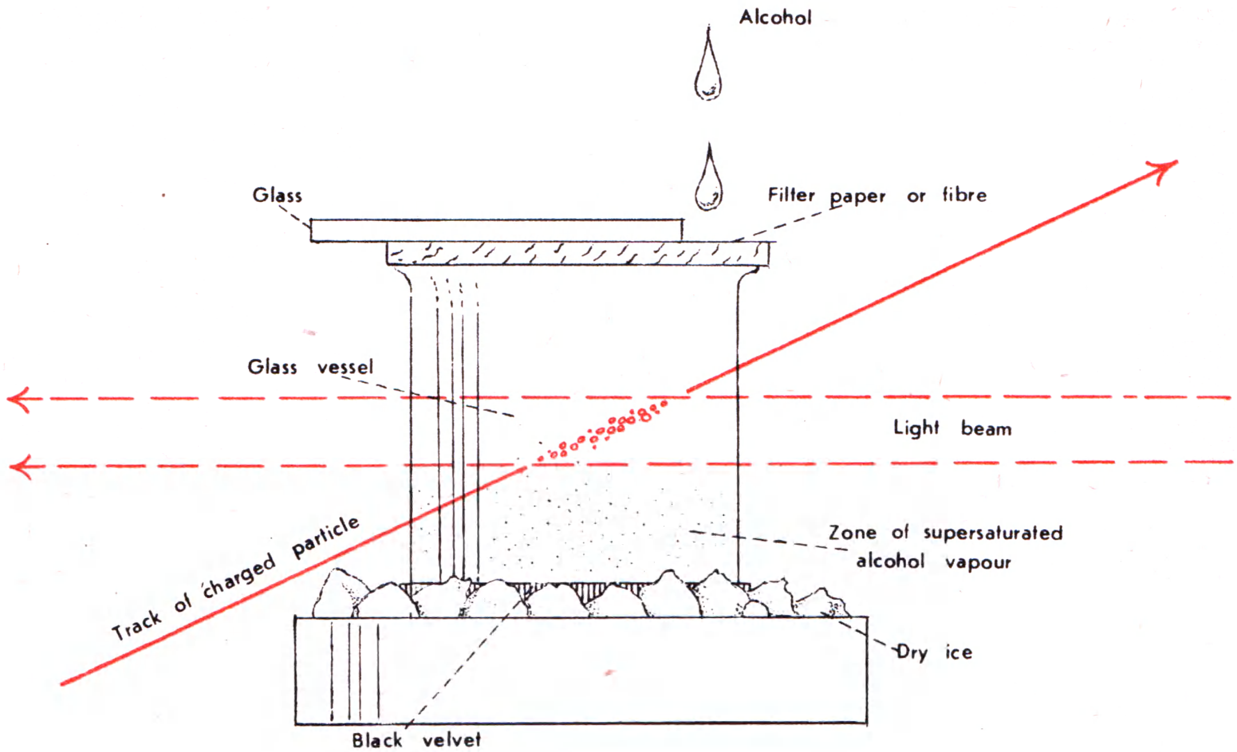
'Cold Boiling'

Nuclear physicists more and more have to deal with unusually fast particles. When such particles enter a Wilson chamber or a diffusion chamber, they leave such a short, weak, and undeviating track that it cannot be measured with sufficient accuracy. As a result much very important and interesting information about them escapes observation. What is more, as the gas filling a Wilson cloud chamber expands slight eddies and currents are set up that distort the track of the particle observed, even though slightly. It is the same as with smoke rings, which very quickly become distorted under the pressure exerted by the imperceptible motion of the air particles in a room.

On any photograph of the traces left by particles as they pass through a Wilson cloud chamber, one can usually see a great number of lines or tracks crossing it in various directions. It is often very important to know exactly in precisely what order these tracks occurred, which passed above or close to others and which passed below or further away.

The Wilson chamber does not answer these questions and certain other ones. How could it be made to furnish this information? Boiling came to the rescue.

For a long time it was thought that the process of boiling liquids and all



The diffusion cloud chamber seems simpler than simple.

phenomena associated with it had been studied quite well, and that nothing unexpected took place during it. The tea kettle boils, steam pours continuously from it, and everything is clear and understandable. But it turned out that so familiar a phenomenon as the boiling of liquid was not quite as simple as it seemed at first glance. What, for instance, is the first sign of boiling? The appearance of bubbles. But how do they form and where? Almost no one had paid any attention to that. The formation of bubbles turned out to be of great and decisive importance in the physics of boiling liquids. We have only to recall the vast number of machines of every kind that work on steam, and the processes based on evaporation.

Experiments showed that vapour bubbles formed mainly on the walls of the vessels in which the liquid was heated, but only at spots where there were irregularities of the surface, depressions or projections that could not in practice be eliminated even by the most careful grinding or polishing. These irregularities served as centres for the formation and growth of bubbles.

When a liquid contains suspended particles of a solid or a dissolved gas, they too serve as centres for the formation of vapour bubbles. But when very pure water is heated in a vessel with ideally polished walls from which even the slightest shock or vibration is excluded, its temperature can be raised to 150° or 180°C with no signs of boiling. But if this superheated water is disturbed, however slightly, it will boil instantly.

This phenomenon suggested the idea to physicists of using superheated liquid in a cloud chamber instead of invisible vapour, and gave birth to a new instrument, the bubble chamber.

When a charged particle passes through a superheated liquid and ionizes its molecules, these molecules become the kernels of bubble formation all along the particle's track, that is to say, the liquid begins to boil instantly along this track. And if we are quick enough to photograph the event we shall find chains of microscopic bubbles, like those observed in an ordinary cloud chamber, on the developed plate.

Another method can also be used. It is known that the boiling of liquid can be delayed by increasing the pressure in the space above it. If this pressure is quickly reduced, boiling does not happen immediately but only after a certain interval of time (short, of course). The tracks of the particles passing through the liquid during this period of quiescence can also be photographed.

The gas filling a bubble chamber is liquefied and being under great pressure is ideally transparent. But when its pressure is reduced to the critical value at which the liquid does not boil simply because there are no centres (i.e. dust particles, charged particles, etc.) in it to promote the formation of bubbles, then any charged particle passing through this supersensitive liquid (which is instantly ready to boil) will leave an ionized track densely covered with gas bubbles and so visible.

What are the advantages of a chamber with superheated liquid over an ordinary cloud chamber?

Any liquid is much denser than water vapour, and therefore slows down particles passing through it much more, so that their ionized tracks are shorter and thicker, and more readily observed and measured. Bubbles form much faster in superheated liquid than in vapour, so that the track left by a particle is much less distorted. And finally, what is very important and is the main advantage of the bubble, chamber, the bubbles of vapour, once they form around the ionized particles of the liquid, continue to grow. And from their size on photographs it is possible to determine accurately which tracks came first and which later.

A 'superheated' liquid is not always one heated to a high temperature. There is an enormous number that 'boil' and turn into vapour not simply at room temperature, but at temperatures considerably lower or with a slight drop in external pressure. Liquid hydrogen, propane, isopentane, and other gases are examples.

The bubble chamber has no pistons or other moving parts, and can be built several metres long, which is just what scientists needed.

A 'Lilliputian Thunderstorm'

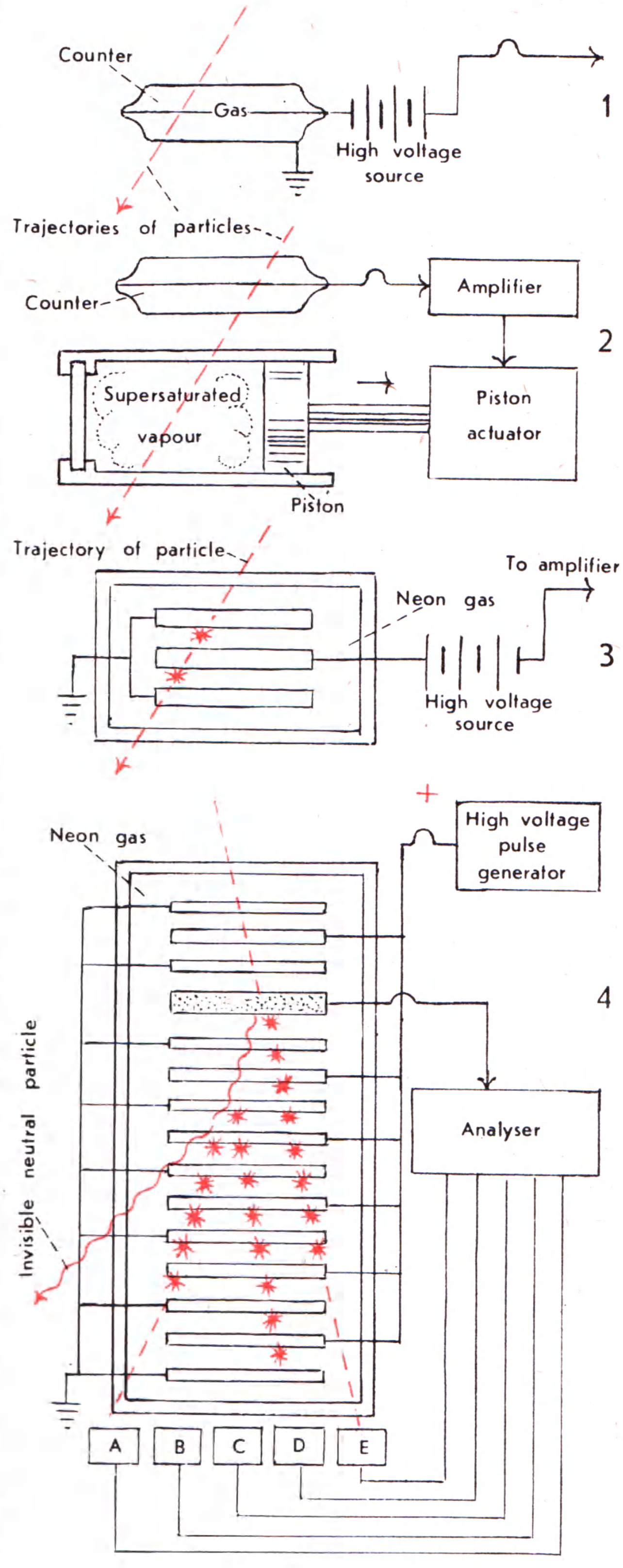
The common shortcoming of all these chambers is that particles are investigated in them by mere guess-work; a great number of photographs is taken, tens of thousands sometimes, in the hope that among the infinite variety of particle tracks on them, there will be one that shows by chance either the track of the particle one is looking for, or that of something new and still unknown.

It is often necessary not only to single out and photograph particles whose properties, e.g. energy, velocity, charge or mass, are known, but also to count them. It then proves of greater advantage to use what is called the *spark chamber*.

The spark chamber is a vessel containing gas under pressure and fitted with two parallel electrodes across which a high voltage can be applied. It resembles an ionizing chamber in certain respects. As soon as even a single charged particle capable of ionizing a substance

in the gap between electrodes enters that gap, a high voltage is automatically applied to the electrodes and instantly causes a microscopic electrical discharge or spark. If the spark is photographed on a single plate by means of a high-speed camera, the plate will show a broken line made up of a multitude of small luminescent points, indicating the track of the particle through the chamber. Three-dimensional photographs can also be made.

A special electronic device attached to this chamber makes it possible to determine with great accuracy the position of a luminescent point (and, consequently, of the particle itself) in space, and also the velocity and direction of the particle, and from that to determine its energy, mass, charge, and other properties.



The genaeology of the spark chamber and how it works. *1*—Geiger-Müller counter; *2*—Wilson cloud chamber; *3*—spark counter: A high direct-current voltage is applied to a metal plate located between two earthed plates. A charged particle passing through the instrument causes an electric discharge in the gas (neon) across the gap between the plates; *4*—spark chamber. A large number of metal plates, alternately connected to one another, are set in a neon-filled vessel. The passage through the chamber of charged particles satisfying certain requirements of the experiment is detected and recorded by appropriate counter *A*, *B*, *C*, *D*, etc. and a special electron logic circuit. When a charged particle passes through the electrode of the common spark counter *a*, a high-voltage pulse is fed to the even-numbered plates, with the result that there is a chain of sparks between the plates along the ionized tracks left by the particle. In our diagram a charged particle has interacted with the material of the electrode component of the spark counter *a*, giving rise to secondary particles, one neutral and one charged (which is recorded by counter *E*). After travelling a certain distance the secondary neutral particle disintegrates, producing, in turn, two charged and one neutral particle. Counters *A* and *D* have recorded the appearance of these two third-generation charged particles

Again That Photographic Plate

You will remember that Becquerel discovered radioactivity from the effect produced by radiation on a photographic plate. In 1909-11 it was shown that the darkened spots appearing on a developed plate exposed to alpha-particles consisted of individual darkened grains of silver, arranged in short chains. The chains indicated and corresponded to the passage of alpha-particles in the emulsion covering the plate.

Photographic emulsion resembles a cloud chamber in that we can record practically any process involving atomic nuclei and other charged particles with it. The thickness, length, shape, and number of the tracks, and their order of appearance, permit us to determine the energy, charge, and mass of the particles.

Photographic emulsion was used for the first successful observation of various forms of disintegration of the atomic nuclei of silver bromide when hit by high-energy particles, and to determine the physical properties of the fragments formed.

Since ordinary photographic plates are of little use for very fine and complicated nuclear research, the Soviet physicist L. V. Mysovsky suggested using special thick emulsions (without backing) containing ten times as much silver bromide as usual.

High-energy particles are investigated by using thick stacks made up of a large number of such 'stripped' or 'nuclear' emulsions, which enable continuous three-dimensional tracks to be observed in a large volume. The layers are separated for development, and then joined together again. The developed layers are usually studied by means of a binocular microscope and special measuring devices.

Larger Calibres

The numerous experiments devoted to bombarding atoms with charged particles showed that the energy of the particles emitted by the atoms of natural radioactive elements was clearly insufficient for the purpose. The problem was how to increase the velocity, that is the energy, of these 'atomic projectiles'.

This much was quite clear. The larger the energy of a particle, the deeper it would penetrate into the nucleus, and the more difficult it would be to deflect it from its path.

Scientists began to design special machines, *particle accelerators*.

We already know that a charged particle can be accelerated by an electric field, and can be deflected by it or by a magnetic field. As a consequence of that the development of accelerators followed two main trends. At first apparatus were built, in which charged particles, moving along straight lines, were accelerated to the maximum possible energy. These devices resembled a much enlarged cathode-ray tube, to the electrodes of which a full accelerating voltage of tens and even hundreds of thousands of volts could be suddenly applied and all at once. Later, it proved more convenient and of greater advantage to use devices in which the particles accelerated in the electric field were forced by means of a magnetic field to move in a circular path. And since the radius of its circular path increased continuously as the particle was accelerated, eventually, in an accelerator of this kind, the particles were forced to move in a spiral path.

These devices came to be called *cyclic accelerators.*

It is extremely difficult, complicated, and costly, however, to obtain a voltage of six or eight million volts, even using huge and very intricate units to

accumulate electric charges. The energy of the alpha-particles emitted by polonium-210, for instance, is 5.26 MeV. Consequently, compared with natural radioactive elements, particles artificially accelerated by means of these superhigh-voltage generators gave no advantage whatsoever. For that reason it became common practice with both linear and cyclic accelerators to accelerate particles not in one step by means of a pulse produced by the highest possible voltage, but by means of repeated pulses of comparatively low voltage.

Everyone knows that even a child can easily sway a heavy swing to and fro if he pushes it repeatedly, and strictly in time with its movement.

Let us first consider a *linear accelerator*. It is a straight tube several metres long (even several kilometres long in some installations), from which the air is completely evacuated. Inside the tube are located a large number of small metal cylinders, one after the other each one longer than the preceding one. Positively charged ions from an ion source are first accelerated by means of a small accelerating tube to an energy of the order of 100 000 to 200 000 electron-volts, then directed into the linear accelerator proper. To every two cylinders a comparatively low alternating voltage is applied from a special high-frequency generator. The voltage changes continuously both in magnitude and sign, being first positive and then negative.

The main purpose of the high-frequency generator is to vary the voltage supplied to the electrodes, so that velocity of the charged particle subjected to the potential difference will increase continuously. That can be only achieved if a high negative voltage is applied in front of a moving positively charged particle each time it passes through any electrode gap. It is rather like the story of making a lazy donkey move by dangling a carrot in front of his nose. The faster the donkey tries to get it, the quicker the desired dainty escapes it.

When a positively charged particle approaches each successive electrode-cylinder, it is necessary that the potential applied to it should be as negative as possible and attract the particle. As it leaves the cylinder the potential should change and become the maximum positive, so that it kicks the particle on. And at that moment the maximum negative potential should be applied to the next cylinder, and so on.

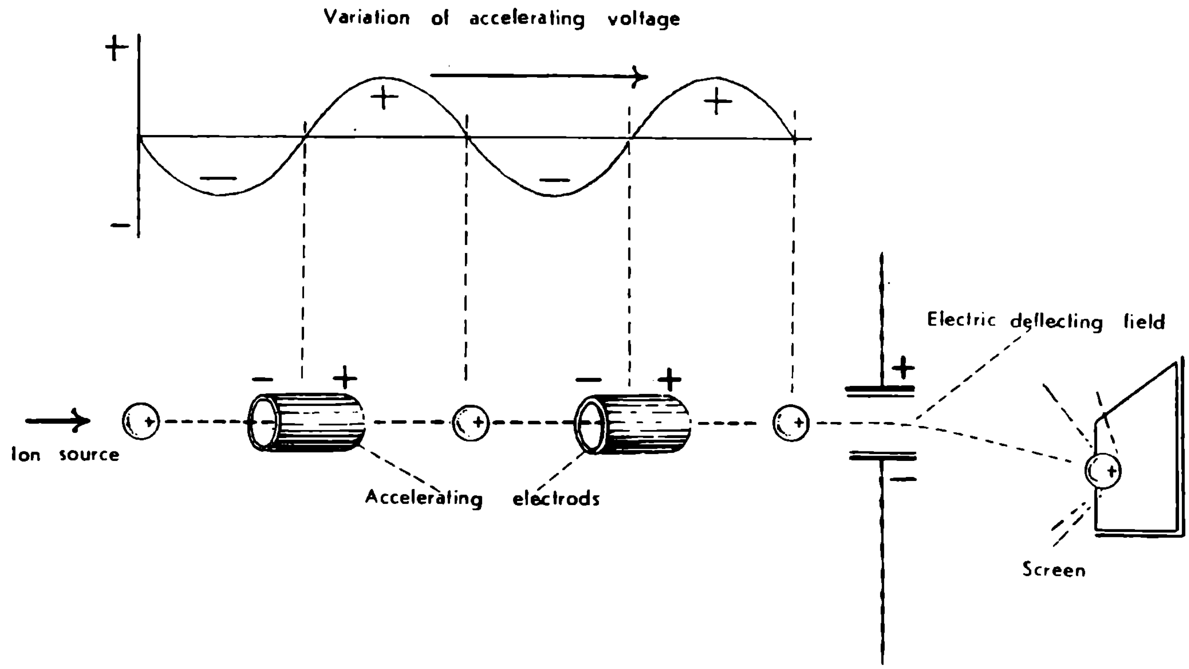
If the sign of the voltage applied to the cylinders is not changed in step (resonance) with the movement of the particle, the particle will be slowed down instead of being accelerated.

Since the velocity of particles is increased continuously in the accelerator, and the frequency of potential alteration remains constant at each pair of electrodes, the successive cylinders are made longer and longer, since the accelerating voltage affects the particles only in the gap between them. Within the cylinders, the particles, isolated from the effect of the electric field, move at a constant velocity, and are said to 'drift' in them.

In this way, by many 'whipping' blows in the accelerating gaps, scientists succeeded in imparting energies of tens and hundreds of millions of electron-volts to positively charged particles, and of hundreds and thousands of millions of electron-volts to electrons.

A linear accelerator works the better, the more thoroughly air is evacuated from it. The vacuum apparatus fitted to it is therefore extensive and complicated.

The accelerated flux of particles passes out of a linear accelerator through a narrow port at its far end, and is directed into specially designed units for irradiating substances being investigated.



The acceleration of particles in a linear accelerator, as it is called. As its velocity, and hence its mass, increases the accelerating electrodes must be made longer and longer

Exactly the same results can be obtained in a rather different way.

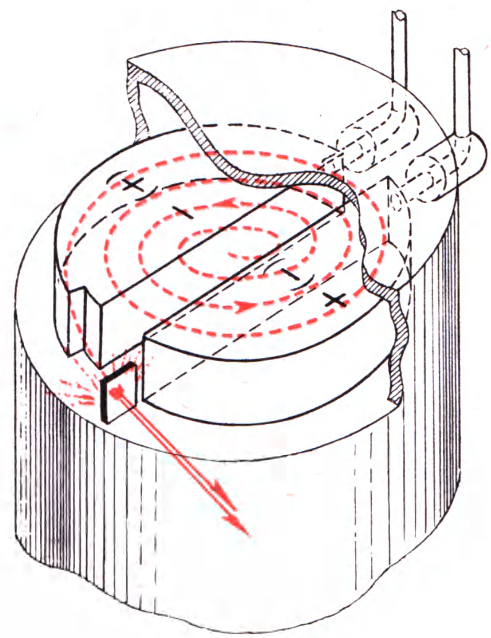
You already know that a charged particle moving along a straight path is deflected from that path when it enters a magnetic field, and if the field happens to be strong enough, the particle begins to 'wind' along on the lines of force of this field as if caught by a peculiar magnetic 'trap'. Now, if accelerating electrodes are placed in the circular path of such a particle and a comparatively low positive and negative voltage is alternately applied to these electrodes as in a linear accelerator, and in time with the revolutions of the particle, the particle will be gradually accelerated, as it crosses the gaps between electrodes. Its movement can be arranged in two different ways: in one it will move in a spiral of increasing radius as it is accelerated; in the other way it will be accelerated without change of radius, so that it moves as if the tube of a linear accelerator had been bent into a circle, or like a stone swung in a sling.

The simplest form of cyclic accelerator, the *cyclotron*, is a flat circular or rectangular box from which the air has been evacuated. Arranged inside it is a flat circular copper chamber, resembling a cheese, or rather its hollow outside rind. The chamber is divided into two halves, and these halves, known as *dees*, are positioned a few centimetres apart. The whole thing is supported in the gap between the poles of a very strong electromagnet.

In the very centre of the chamber, in the gap between the dees is the device used to inject the charged particles (e.g. protons, or ionized hydrogen nuclei) to be accelerated.

A high-frequency alternating-current generator is connected to the two dees in such a way that as soon as one has a high positive voltage the other has a negative one of the same magnitude.

At the next moment the voltage is switched over, so that the electrode that was positive becomes negative, and the one that was negative, positive. This is repeated many times. The flux of protons passing across the electrode gap is drawn to the negatively charged dee, and kicked onward by the negative charge of the dee being left. In that way the flux acquires a certain initial velocity. Having made a semi-circle inside the dee, the protons come again to the accelerating gap. At that moment the sign of the voltage applied to the dees changes, and the particles are drawn to the opposite, now negatively charged dee, whipped on by the present positive charge of the previously negatively charged dee. After having travelled another half circle inside the second dee, the particles again reach the electrode gap, and again the voltage applied to the dees changes, and the whole cycle of alteration of voltage in the dees is repeated once more.



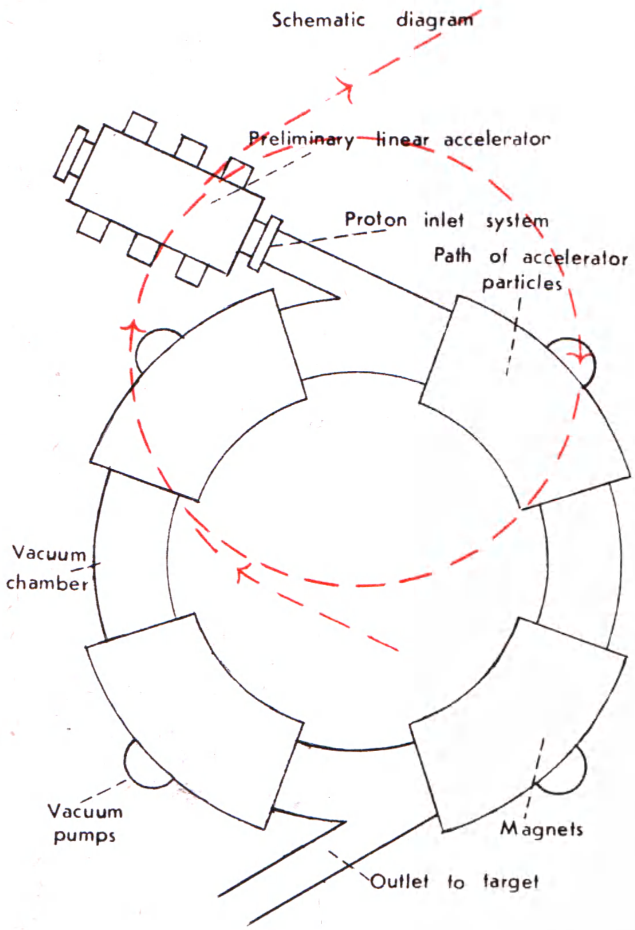
Moving in a spiral in the alternating electric field of a cyclotron, a charged particle gradually acquires tremendous velocity. But, as its velocity increases its mass also gradually increases, so that it begins to lag behind the change of voltage across the accelerating electrodes. To eliminate this fault, the frequency of the accelerating voltage is diminished as the velocity and mass of the particle increase

Particles that reach the accelerating gap just before the alteration of voltage are slowed down a little, while particles that do not reach the gap at the moment of the change of voltage lag behind the rest of the particles; because of that, the flux of charged particles injected into the accelerator proves on leaving it to be divided as it were into portions or bunches.

The particles accelerated to the maximum possible velocity are discharged from the accelerator by means of a special deflector, and are aimed at a target made of the material to be bombarded.

The process of acceleration, and consequently the increase in energy, of particles in the cyclotron could be repeated an infinite number of times, if it were not for the following essential circumstances. As the velocity of particles approaches that of light, what is called the *relativistic effect* begins to take place, that is to say their mass is substantially increased; and it becomes more and more difficult to increase their velocity; their radius of rotation gradually increases and they begin to reach the acceleration gap more and more in retard of the change of voltage in the dees so that the impulses of acceleration coincide less and less with their rhythm. The accelerating and whipping effect of the alternating voltage in the dees weakens at the same rate, and is gradually brought to nought. These two circumstances make it impossible to accelerate charged particles to energies exceeding 10-20 MeV.

Such energies, several times greater than those of the particles emitted by radioactive substances, suited scientists very well, and cyclotrons therefore be-



The Soviet synchrophasotron, which accelerates particles to an energy of 10 GeV

come obligatory equipment of the world's main research laboratories. But very soon scientists became convinced that even these energies were insufficient.

And it is difficult to say how physics would have developed, if two scientists, V. I. Veksler in the USSR and E. M. McMillan in the USA, had not simultaneously had the same idea as follows. If because of this relativistic mass, accelerated particles enter the accelerating gap late or out of phase with the maximum alternating voltage applied to the dees, why not vary the frequency of the alternating voltage at a rate similar to that at which the mass of the particle increases and consequently its acceleration is slowed down. Then, no matter how much it slowed down, the maximum voltage applied at the strictly prescribed moment would not brake it, but would still spur it on. The particle would begin to follow the field as it were crossing the accelerating gap at the moments that are most favourable for its acceleration. And although its rate of acceleration would gradually decrease with each revolution, its absolute velocity would increase, approaching the velocity of light. This method of acceleration became known as the principle of phase stability.

In this way it was possible to overcome the limitations imposed by relativistic mass, which limited the maximum energy of particles accelerated in a cyclotron, and so to obtain protons with an energy of several hundred million electron-volts.

In installations of this kind it is impossible to accelerate a continuous flux of particles and they must be injected into the accelerator in strictly limited portions. So these machines became known as *synchrocyclotrons* or *phasotrons*.

The experience gained by scientists in building cyclic accelerators showed that it was possible to accelerate particles to still higher energies, provided that, instead of moving in spirals, particles were accelerated as they moved along a so-called equilibrium orbit of constant radius. This proved possible in units with a variable magnetic field. The strength of the magnetic field is periodically increased and then reduced to some initial magnitude, i.e. for every increase in the strength of magnetic field there is a quite definite increase in the frequency of the accelerating electric voltage, so that the particle, whipped along by the accelerating voltage, moves in one and the same orbit.

	Constant magnetic field	Modulated magnetic field
Constant frequency of the accelerating voltage	Cyclotron	Synchrotron
Modulated frequency of the accelerating voltage (gradually decreasing)	Synchrocyclotron	Synchrophasotron

That made it possible to have a magnetic system in the form of a ring built from individual electromagnets or of a ring in which the component electromagnets were arranged in sections at only a few spots or even at only one place. Accelerators of this type are called *synchrotrons* or *synchrophasotrons*.

The first accelerators were imperfect. They gave particles of low energies under 100 000 electron-volts. But even that was a great achievement for nuclear physics and engineering, and showed the amazing flexibility of human thought. But in order to attain the goal set by scientists it was clearly not sufficient.

In 1929 accelerators began to be built that made it possible to accelerate particles to energy exceeding that of the particles emitted by radioactive elements. By 1935 the energy of accelerated particles had been raised to 5 MeV, and in 1945 appeared accelerators that enabled energies of 200 MeV to be obtained.

The invention of synchrophasotrons immediately raised the upper limit of charged-particle energy. By 1955 accelerators rated at 2 300 and 6 200 million electron-volts had appeared in the USA (2.3 GeV* and 6.2 GeV), and in 1957 a Soviet-built synchrophasotron of 10 GeV began functioning in Dubna, which remained for some time the most powerful accelerator in the world. And later more powerful synchrophasotrons were built in Switzerland (30 GeV) and at the Brookhaven Laboratory in the USA (33 GeV). And in Serpukhov, near Moscow, an accelerator has been built with an energy of 70 GeV, and is at present the most powerful in the world. Its circumference is 1.5 km long, and its 120 magnets weigh 24 000 tons!

* GeV = gigaelectron-volts, i.e. 1 000 MeV.

In order to make it easier to understand the modern types of cyclic accelerators we have drawn up a table (see at the top of this page).

Various kinds of improvements to these basic types provide cyclic accelerators for the most diverse purposes, for example, to accelerate electrons (betatrons), to accelerate alpha-particles and multicharged ions (nuclei of atoms heavier than helium), etc.

In the not so distant future the power of heavy 'atomic artillery' created by men will come close in power to the energy of the cosmic 'projectiles' that fall on our planet from the infinite depths of the universe.

The investigations carried out by scientists using accelerators, and the amazing and exceptionally important results obtained by them, are of such scope and interest that to describe them calls for another book. And to tell about them here, even briefly and sketchily, would divert us from our main theme. But we shall return to some of the problems later.

At New Cross Roads

The calculations made by scientists by 1928 had shown that the most suit-

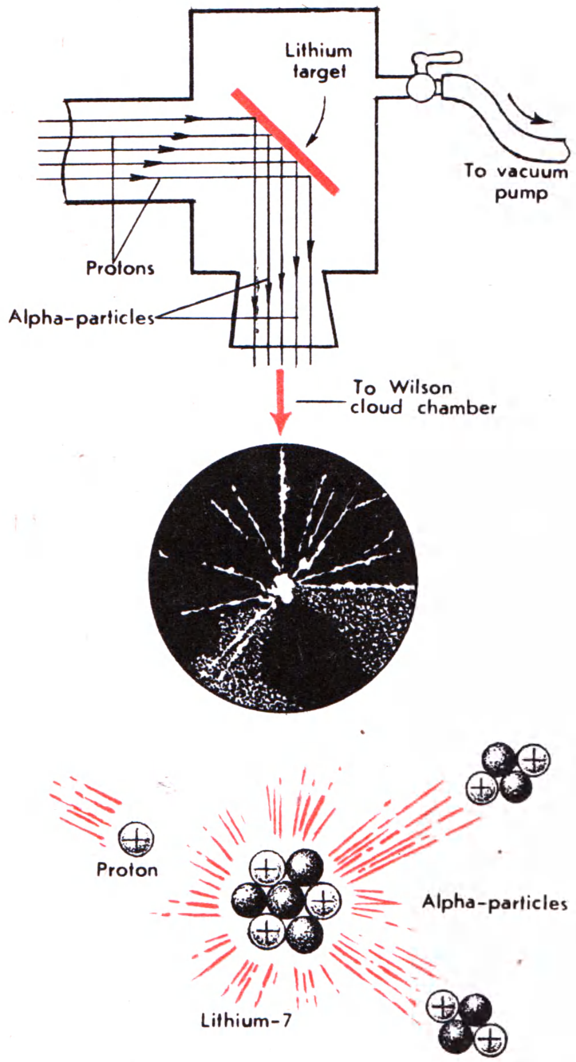
able 'projectile' for bombarding atomic nuclei was the fast moving proton.

There were many reasons for that. The proton is a quite heavy particle, so that it is easier to hit the nucleus of another atom with it. It is also easier to accelerate than, say, an alpha-particle which may strike you as strange and incomprehensible. Surely it would be easier to accelerate an alpha-particle, for its electric charge is double that of a proton, and when subjected to the same potential difference, it therefore acquires twice as much energy. But, the repulsion effect of the total positive charge of an atomic nucleus is less when it is approached by a particle carrying only one positive charge and not two.

Thus, protons, accelerated to high energies, are more effective 'projectiles' for atomic artillery than alpha-particles. Bearing that in mind two Cambridge scientists, the English engineer John Cockroft and the Irish physicist Ernest Walton, had already reported in 1932 an experiment that was to play a very important part in present-day physics.

The experiment consisted in using protons, accelerated in an accelerating tube to an energy of the order of 0.125 MeV, in a narrow beam to bombard a target made of lithium-7. The particles resulting from the bombardment were passed into a Wilson cloud chamber in order to determine their charge, mass, and velocity.

The results of the experiment were quite unexpected. The atom of lithium



The atom of lithium, hit by a proton, splits into two alpha-particles

Mass of lithium nucleus Proton	7.0182 atomic units 1.0081 atomic units
Mass of the particles involved in the reaction	8.0263 atomic units
Total mass of two alpha-particles (4.0039 + + 4.0039)	8.0078 atomic units
Difference	0.0185 atomic units

reacting with the proton hitting it, turned first into an isotope of beryllium that disintegrated at once, however, into two nuclei of helium, or alpha-particles, each of which acquired an energy of the order of 8.6 MeV!

$$_1H^1 + {_3Li^7} \rightarrow {_4Be^8} \rightarrow {_2He^4} + {_2He^4}$$

This time it was not only the result that troubled the scientists, but another, even more important circumstance. When they tried, with a pencil and paper, to draw up a balance of the energies, masses, and velocities of all the particles involved in the reaction, a whole number of really amazing gains and losses were revealed.

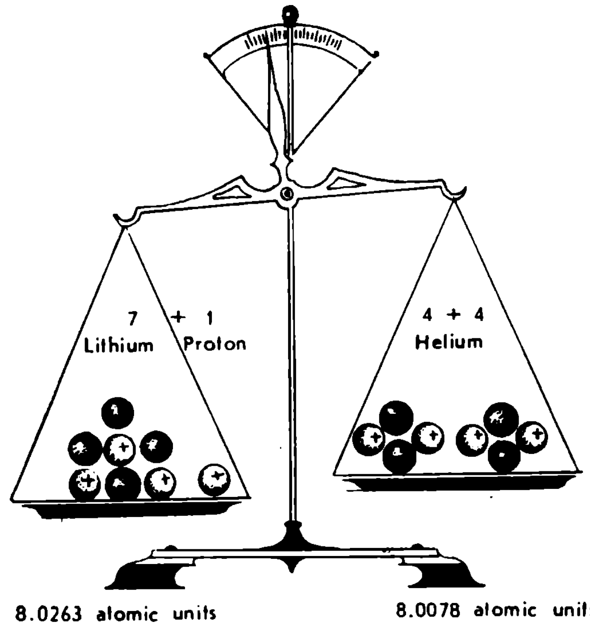
Not only had certain nuclei been transmuted into others before their very eyes, but a mass constituting the difference between the initial and final states of the matter involved in the nuclear reaction had disappeared somewhere.

The difference, as we can see, was quite tangible. What was it, a breach of the law of conservation of mass and energy?

Where could all this mass have gone?

On the other hand there was an excess of energy of 17.2 MeV in the form of the kinetic energy of the two alpha-particles produced by the nuclear reaction, which much exceeded the energy of the protons used to bombard the lithium nucleus.

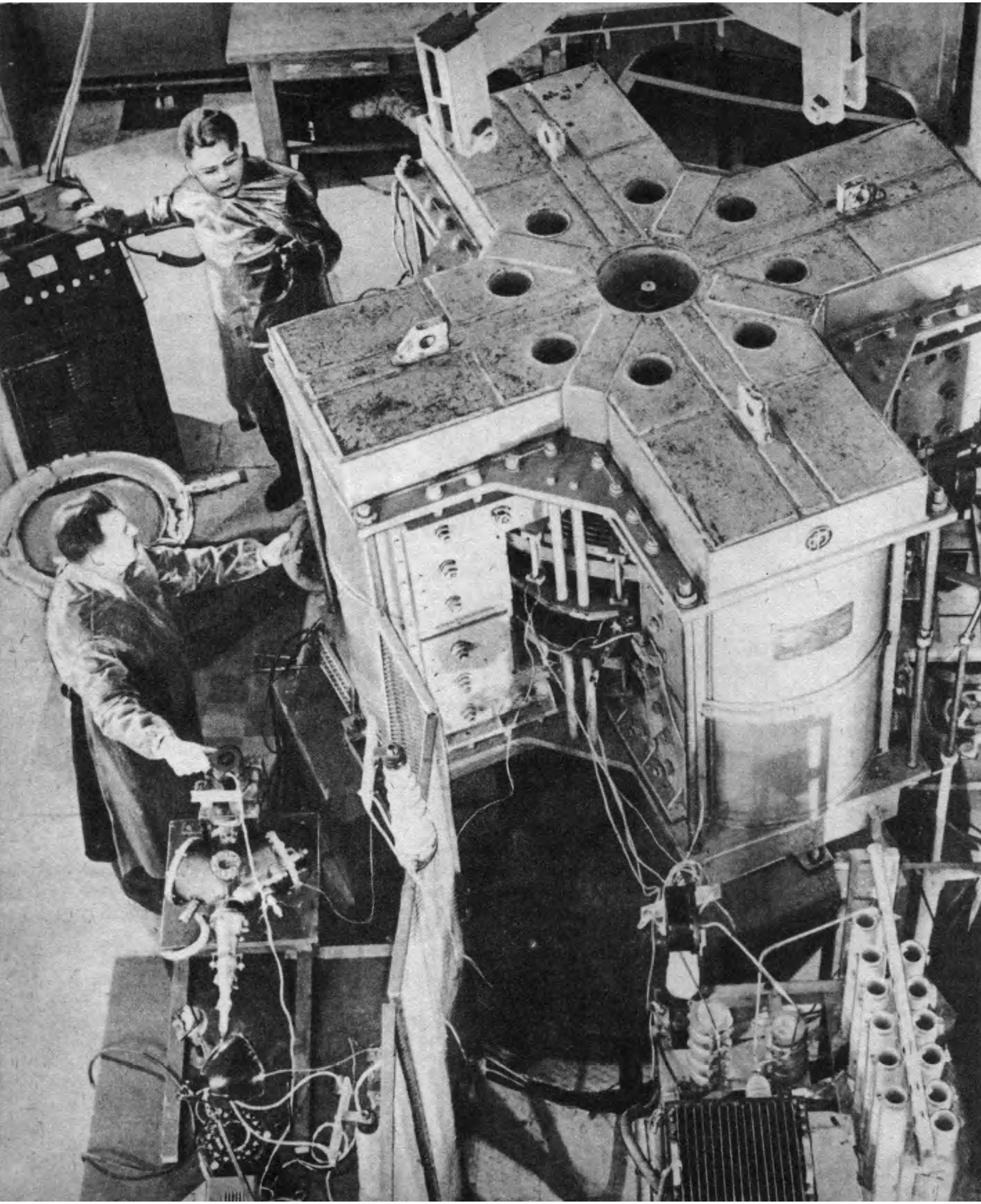
Naturally, this suggested the following conclusion: either matter had been converted into energy, which was nonsense, since energy was only a form of existence of matter, because only a physical reality, i.e. matter, could move; or, and this was the only assumption that could be correct, mass and energy were two forms of the existence of matter. In accordance with the laws of conservation of mass and energy, a decrease of one of them should be compensated somehow based on strict physical laws by an increase in the other.



When a lithium nucleus is converted into two helium nuclei a mass, equal to 0.0185 atomic units, vanishes somewhere. But where?

These experiments and conjectures indicated the direction physicists should take in their search for new sources of energy, the more so, since long before Cockroft and Walton's experiments many similar problems had been brilliantly suggested by theoretical physicists.

It was necessary to look for nuclear reactions in which the mass of the products would be smaller than the total mass of particles involved in the reaction. And such reactions were found, many of them first on paper and then in the laboratory.



Chapter Five

THE KEY TO THE ATOMIC NUCLEUS

New Radiation

Study of the phenomena of radioactivity made it possible at that time to draw the first approximate deductions about the structure of the atomic nucleus. Scientists believed that, in addition to protons, the nucleus contained electrons that neutralized the charge of the protons. This was also indicated by beta-disintegration: the nuclei of radioactive elements emitted quite real electrons.

Everything seemed correct and convincing. But as science progressed, other discoveries made it more and more clear that there were no electrons in the nucleus.

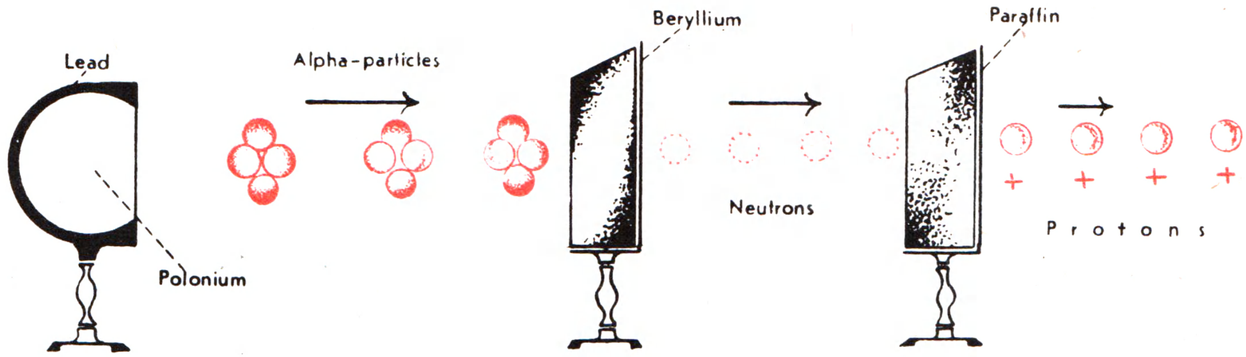
It was a new puzzle in what had seemed a clear and comprehensible matter. And this puzzle could only be solved by assuming that, instead of electrons paired with some of the protons, the nucleus contained particles of a mass equal to that of a proton, but without an electrical charge.

This idea was so tempting that it was suggested independently in 1920 by three different physicists: Rutherford in England, Masson in Australia, and Harkins in the USA. Harkins even suggested the name 'neutron' for this yet undiscovered particle.

The methods and research tools then available, however, made it impossible to discover a particle that had no electric charge.

So, the question of its existence hung long in the air, until physicists ran across an incomprehensible phenomenon in 1930.

Unexpectedly! Suddenly! These words often begin the descriptions of the very dramatic events that lead scientists and inventors to the greatest and most important scientific and technological discoveries, and after reading stories about several such cases, the reader either con-



The experiment that led to discovery of a new particle, the neutron. Atoms of beryllium, absorbing alpha-particles, eject unidentified neutrons. The latter, hitting nuclei of hydrogen in the paraffin, knock protons out of them that can be identified and recorded by Geiger-Müller counters

cludes that most of these discoveries have been made by mere chance, or he rightly suspects that the authors of the books attach too much importance to chance, rather than to creative foresight.

Yet everything seems to happen by chance: Roentgen discovered X-rays by chance; Becquerel discovered the phenomenon of radioactivity by a mistake, and so on. And when one thinks of how most discoveries, great and small, were made, they were all to some extent accidental, or rather, they happened rather unexpectedly during a series of experiments and searches that led inevitably to them. And if some discovery or another had not been made by a certain scientist, it would have been made by another scientist, or by their pupils, or it would certainly have happened during the lifetime of the next generation. The point is that Roentgen was studying the properties of a flux of fast electrons. And Becquerel had made it his task to solve the mysterious luminescence of a section of the cathode tube.

Suppose you are setting off to investigate an unknown region. Everything will be of interest to you, the landscape and nature, the plant and animal kingdoms, and much else—in short, everything you find there. Romantic fancy draws pictures of possible discoveries one more alluring than the other. Then you cross a ridge and before you opens an amazingly beautiful lake.

Unexpected? Yes. Suddenly? Of course. But, although you did not suspect it, it was just such a lake that you had set out to find when you took your first step at the beginning of the journey.

Therefore we would ask you to excuse us if, as we go along, we wax enthusiastic about some discovery or another and begin our description from time to time with an 'unexpectedly' or a 'suddenly'.

So, looking for approaches to the mysterious atomic nucleus, or even for scarcely visible tracks leading to it, the German scientist W. Bothe and H. Becker were puzzled in 1930 by something quite contrary to what they had expected to find when they began their experiment. Studying the interaction between 'atomic projectiles', alpha-particles with an energy of the order of 5.26 MeV emitted by polonium-210, and the atoms of light elements, they bombarded lithium, beryllium, and boron, the nuclei of which contain, respectively, three, four and five protons. Bothe and Becker wanted to see what would happen to

them when they were hit by a 'projectile', a nucleus of helium, of comparable mass.

Quite strange things in fact happened. The bombarded elements began to emit very weak but amazingly penetrating radiation.

Over the next two years scientists in many countries experimented with this mysterious radiation. The daughter of Marie and Pierre Curie, Irene Curie, and her husband, Fréderic Joliot revealed another curious fact, that soon became of help in finally explaining both the nature of this radiation and the structure of the atomic nucleus.

They put a screen of paraffin in the path of the new radiation, and hydrogen nuclei, or protons, began to be ejected from it, being knocked out by the mysterious radiation. It was quite impossible for alpha-particles to knock protons of such energies out of paraffin. To do so, they would need to have an enormous energy, not less than 50 MeV.

In that case what was this mysterious radiation?

Enter the Neutron

It was only at the end of 1932 that the English scientist James Chadwick, having conducted a series of similar experiments, at last succeeded in proving that the new radiation in fact had nothing in common with gamma-rays, but was a flux of neutral particles, whose mass coincided with that of protons.

These particles were the previously predicted neutrons.

Particles with such a mass were quite able to knock hydrogen nuclei out of paraffin, and since they had no charge, nothing could prevent them from interacting with the nuclei of the bombarded material.

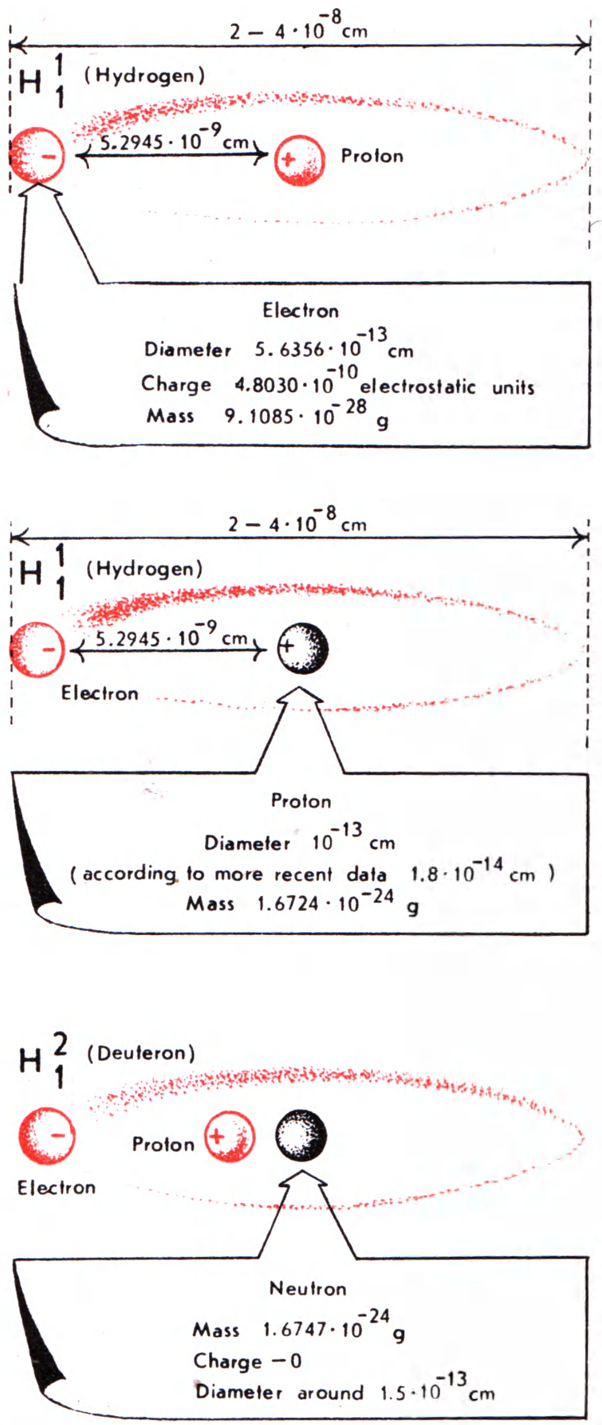
Thus, Bothe and Becker were the first to get on the track of this long awaited particle, so needed by physicists. Its discovery had been delayed so long because of its striking properties, for scientists had no instruments at their disposal by which they could observe a neutral particle.

When charged particles, as we have already said, collide with the atoms of other substances, they first interact electrically with the electron shells of the atoms, an interaction that is accompanied with ionization of the substance, which is recorded by means of appropriate instruments. But the neutron has no electric charge. It quietly passes right through the electron shells of atoms, because they do not affect it in any way; and it is also insensitive to the positive charge of the nucleus.

When a neutron collides with a hydrogen nucleus, it somehow transfers part of its energy to the hydrogen. Naturally, the smaller the mass of the atomic nucleus with which a neutron collides, the greater is the energy transferred. It is therefore best to observe the phenomenon in substances of low atomic weight, and, the lowest atomic weight, of course, is that of hydrogen nuclei. That is why the interaction of neutrons with atomic nuclei in paraffin was so striking, for paraffin contains many hydrogen atoms.

It proved just as difficult to control neutrons as to detect them, again because they had no electric charge. The velocity of a charged particle can easily be altered, and the particle directed as the observer requires by means of electric and magnetic fields, even particles of very great energy. The only thing needed is to create a sufficiently strong field. But the neutron is not affected by either an electric or a magnetic field.

The only way to act on a neutron, i.e. to alter its movement, is to place the nuclei of various elements in its path; when it collides with them its



The 'vital statistics' of the electron, proton, and neutron

velocity will be reduced, and its trajectory altered.

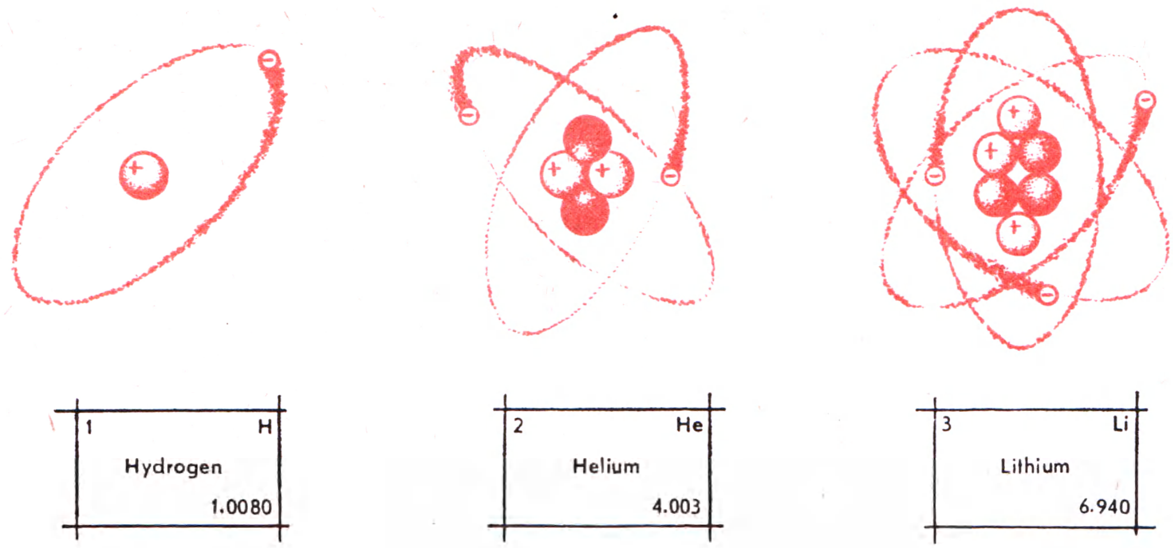
Protection against radiation is usually based on the fact that radiation loses part of its energy when it interacts with the electron shells of the atoms of the material of the protective shield. But neutrons do not interact with these shells. Thick lead plates, which reliably absorb even very strong streams of gamma-rays, do not stop neutrons. On the other hand, a thin cadmium plate, through which gamma-rays easily pass, is an insurmountable barrier for neutrons for they are absorbed by the atoms of cadmium.

We shall return many times to the various interactions of neutrons with matter and their slowing down and absorption, for these are very important problems of neutron physics, which has now become the theoretical basis of a rapidly expanding branch of engineering, nuclear power engineering. Everything connected with neutrons is therefore studied in great detail.

The mass of a neutron almost coincides with that of a proton, almost, but not quite. If we take the isotope of oxygen O^{16} as our yardstick and assume that its mass is 16 times unity, then the mass of a proton will be 1.00759, and that of a neutron 1.00898. The difference is not great, but, as we shall see later, it is very essential.

Free neutrons are 'radioactive'. They cannot remain long in a free state; after a lapse of 11.7 minutes they disintegrate into a proton, an electron, and another particle of zero charge and negligible mass, the *neutrino*.

There are no natural sources of neutrons in nature, apart from a very few that are ejected from time to time during the spontaneous disintegration of uranium nuclei; they also appear in the gaseous envelope of the Earth as the result of collisions in the atmosphere be-



This is how the nuclei of hydrogen, helium, and lithium were envisaged in the theory advanced in 1932 by Gapon and Ivanenko

tween fast charged particles coming from outer space and the atoms of the atmospheric gases.

It is quite easy to produce a stream of neutrons by bombarding beryllium with alpha-particles. For that reason radium-beryllium compounds were used for a long time as the main sources of neutrons after their discovery.

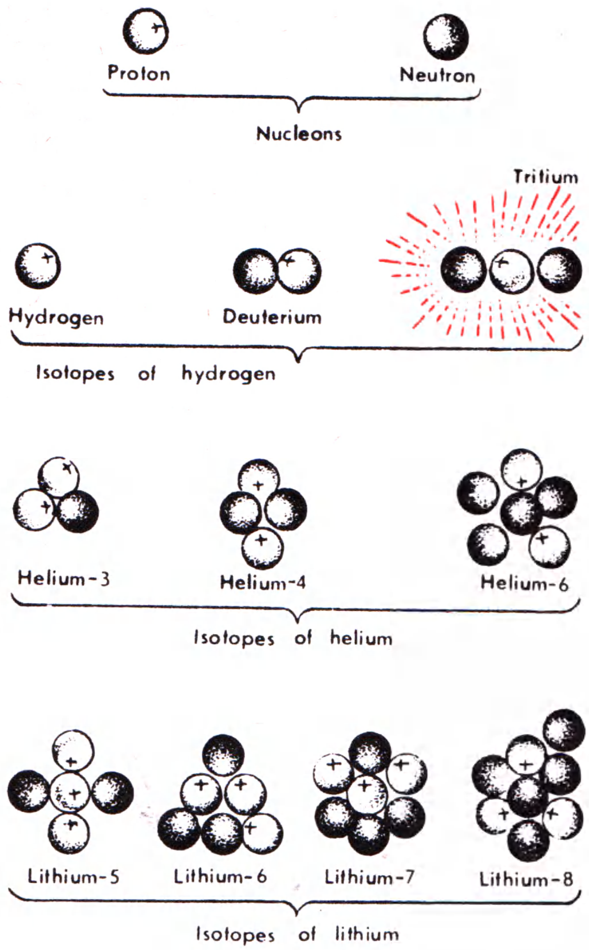
So, we see, the neutron can only be identified by indirect methods. One of these is based on the fact that an ionized particle resulting from collision with a neutron, the *recoil nucleus*, can be detected by ordinary methods. Others are based on the capture of neutrons by the atoms of certain elements, the newly formed nucleus emitting some other charged particle that can be identified, or gamma-radiation, which can be recorded.

The Clue to Nuclear Structure

The discovery of the neutron was probably the most important event in the history of modern nuclear physics. It made it possible to eliminate the very weak link in the chain of ideas concerning the structure of the atomic nucleus that had long been troubling physicists. It had become clear that the nucleus contained no electrons. They suddenly occurred in it only at the moment when the nucleus disintegrated radioactively and emitted an electron. Now, in addition to the proton, the neutron became a main component particle of the nucleus.

A new model of nuclear structure was proposed in 1932 by the Soviet scientists Dmitri Ivanenko and Eugene Gapon, and independently from them by the German physicist Werner Heisenberg. They suggested that the nuclei of all atoms contained only protons and neutrons, which were given the common name of 'nucleons'. The number of protons contained in a nucleus was equal to its total positive charge, i.e. to its atomic number in the periodic system, and the total number of nucleons, protons, and neutrons, to its atomic weight.

The nucleus of helium, for instance, consists of two protons and two neutrons. The positive charge of its nucleus is



The difference in the masses of the isotopes of various elements depends only on the number of neutrons in the atomic nucleus

therefore two, and two electrons rotate in its shell.

And since it has altogether four protons and neutrons its atomic weight is four.

The discovery of the neutron made possible a quite simple explanation of the existence of isotopes. The atomic weight of each isotope of an element depends on the number of neutrons in its nucleus.

Apart from isotopes, atoms of equal atomic weight occur in nature, that occupy different places, however, in the Periodic Table, being atoms of different elements. They are referred to as *isobars* (from the Greek *iso* same and *baros* weight).

So, if one atomic nucleus, for instance, contains five protons and five neutrons, and another five protons and six neutrons, then by the number of protons, i.e. by the number of positive charges (five), both are isotopes of one and the same element, boron, and differ from each other only in mass (atomic weight), the weight of the first being ten, and of the second, eleven.

If, however, we consider two atoms both of mass ten, but one of them containing four protons and six neutrons and the other five protons and five neutrons, these will be atoms of different elements; the first one is an atom of beryllium, and the second of boron.

There are atoms of potassium and calcium of an identical mass of 40, atoms of cadmium with masses of 112, 114, and 116, and atoms of tin of identical mass (112, 114, and 116), and so on.

The radioactive nuclei of certain elements, however, may contain an equal number of protons and neutrons, but these may be arranged differently so that the nuclei as a result are in different states of excitation. This can be detected because, during radioactive decay, nuclei of different degrees of excitation

differ in radioactivity, i.e. have a different half-life. The nuclei of the same artificial radioactive isotope of antimony-124, for instance, may disintegrate in 1.3 minutes, 21 minutes, or in 53.7 days. Such nuclei are known as *isomers* (from the Greek *iso* same and *meros* part).

The nucleon model of nuclear structure was immediately adopted. It agreed with the numerous facts accumulated by that time, explained them, and indicated new directions for scientists in their experimental work; and, as always happens in science, it 'craftily' led to even deeper mysteries, contradictions, and real miracles.

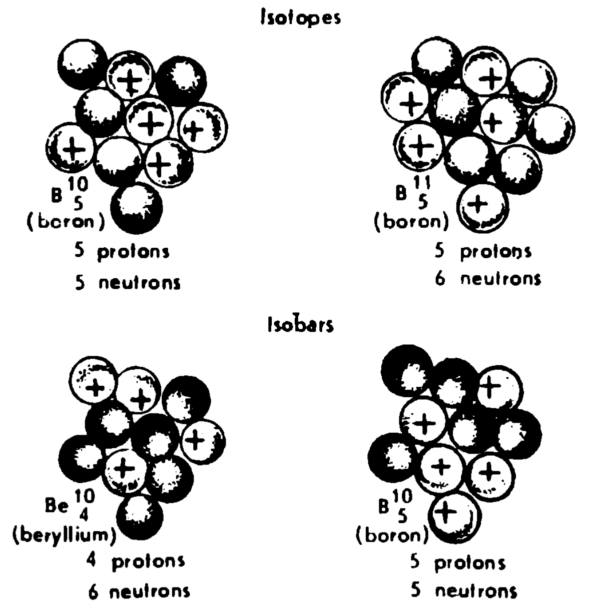
The Cap of Fortunatus

Like any other new scientific theory that brilliantly solves one of the riddles of nature, the nucleon model at once brought to light a good dozen other puzzles, still more intricate and difficult, and at the same time breathtaking and fascinating. That, by the way, is perhaps the main driving force of science.

The proton-neutron theory could not get round the difficulties arising from the existence of the enormous repulsive forces created by the positive charges of protons that are held together in the atomic nucleus by some mysterious force.

What kind of forces, in fact, keep the protons from flying apart in all directions with the velocity and energy of an explosion (within the limits of the atomic nucleus) of unprecedented shattering force? Why do neutrons, which have no charge, not simply fall out of the nucleus?

Mankind has had proof over and over again that there is nothing magic in science, in the world of the most miraculous and mysterious. Sooner or later all phenomena are given a strictly scientific and conclusive explanation. So there was nothing for it but to assume that there were new, still unknown forces operating in the atomic nucleus, many times greater than the forces of electrostatic repulsion, acting between its positively charged protons.



The different number of neutrons and protons in an atomic nucleus explains why nuclei of equal mass (number of nucleons) prove to be isotopes of different elements. Such atoms are called isobars. The drawing illustrates the difference between isotopes and isobars

The existence of these forces could also be explained by enormous power being locked up in the nucleus, and manifesting itself in the decay of radioactive substances, in the ejection of particles when atomic nuclei were bombarded with protons or alpha-particles, and in the transmutation of certain elements into others.

The unknown forces acted in the same way on both charged and natural particles. And it was they that, like a strong spring, retained and compressed the positively charged protons and neutrons into the infinitely small space occupied by the nucleus (1/100,000th of the dia-

meter of an atom). But, apparently, if a nucleus were pushed even so slightly, i.e. if a small quantity of excess energy were imparted to it, then, being saturated with its own energy, it would begin to break up.

That could be tried in two ways. The more difficult way was to attempt to force a heavy charged particle of some sort into the nucleus capable of overcoming the total positive charge of its protons. But the energy of the proton emitted by radioactive boron-87 (10 MeV) was not sufficient for the purpose. The particles spent most of their kinetic energy on overcoming the 'armoured shield' of the nucleus, and, having lost their strength, were unable even to make contact with it, let alone to penetrate it. So it was necessary to accelerate them artificially to considerably higher energies.

The neutron offers quite different, indeed amazing possibilities. Enjoying 'neutrality', it passes freely through the electron shell of an atom and through the zone in which the repulsive forces of the total positive charge of the nucleus act. It was not without reason that Rutherford had prophesied in 1920: "it may be impossible to contain it in a sealed vessel". On approaching close to the nucleus, the neutron comes into the sphere of action of the nuclear forces, and if it is moving slowly enough, is drawn into the nucleus.

And there the most amazing thing begins to happen.

As a result of the unexpected 'addition to the family', the nucleus comes to possess an excess energy of 8 MeV which abruptly disturbs the existing balance of forces, so that it acquires a rapid motion or, as physicists say, an excited state that can only be overcome by throwing off a nucleon, or an alpha-particle, or by splitting into several fragments.

But why does the mere union of a neutron with the nucleus impart an energy of excitation equal to 8 MeV to the latter? We shall only be able to answer that in a later chapter. For the time being let us take it on trust.

If it takes seven or eight electron volts to knock a nucleon out of nucleus, it would be logical to assume that when an extra nucleon is forced into a nucleus, it would acquire an exactly equal excess energy of 7-8 MeV. This energy first excites the nucleus, then causes its disintegration with release of the excess energy.

That being the case, how much excess energy or energy of excitation is required, for instance, to induce fission of an atomic nucleus, accompanied by the release of an even greater amount of energy?

The smaller an atomic nucleus is the heavier it is. For that reason the nuclei of heavy elements are the most unstable. This is clearly illustrated by the following data:

Mass number of an atom	140	200	235
External energy required to excite its nucleus, MeV	62	40	5
Energy released by nuclear fission, MeV	48	135	205

Now if a neutron also possesses a kinetic energy of 10 MeV, then it will give the trapping nucleus an excess energy of 18 MeV and so the nucleus of the 'hospitable' atom will be excited even more.

It turns out that a neutron need hardly possess any initial kinetic energy. The only thing needed is to help it to enter the atomic nucleus. Once there, it will add its own energy to that of the host nucleus, making use in a special manner of its own latent reserves.

Artificial Radioactivity

Attempts to transform the atoms of certain elements into atoms of others by bombarding them with alpha-particles proved most fruitful only when the lightest elements, lithium, beryllium, and boron, were used as targets.

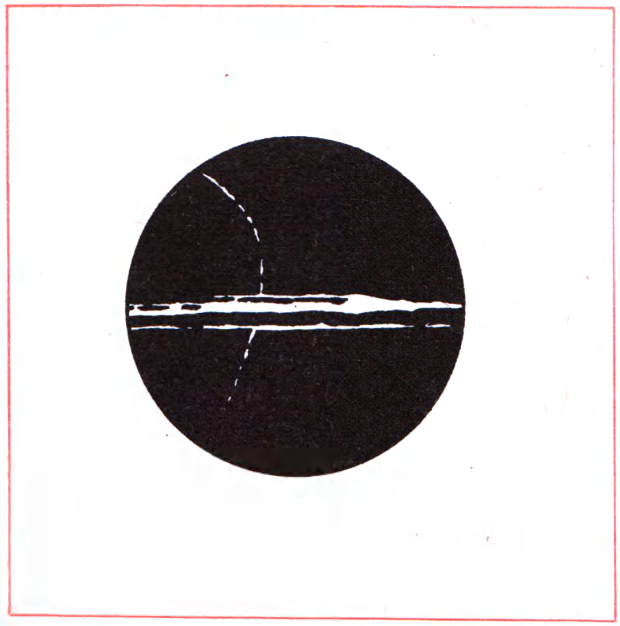
To smash the atoms of heavier elements, the energy of alpha-particles emitted by disintegrating radioactive substances proved insufficient, as we have already said. So it is not surprising that it occurred to scientists that neutrons that were in no way affected by the powerful charge of heavy nuclei, might be used.

But the sources then available emitted too few neutrons. A gram of radium knocked no more than 10^7 neutrons per second out of a beryllium plate. Such a stream of projectiles, even taking the ability of neutrons to penetrate nuclei into account, was clearly much too small.

It was while trying to obtain a much more powerful flux of neutrons, in 1934, that Irene and Fréderic Joliot-Curie discovered the quite new and remarkable phenomenon that became one more basis for modern nuclear physics and technology. They were experimenting with a polonium source, more active than radium, emitting alpha-particles of an energy over 5 MeV.

They had used this powerful stream of alpha-particles to bombard various substances (boron, aluminium, magnesium, etc.), expecting to detect elements among them that would emit the maximum possible flux of neutrons.

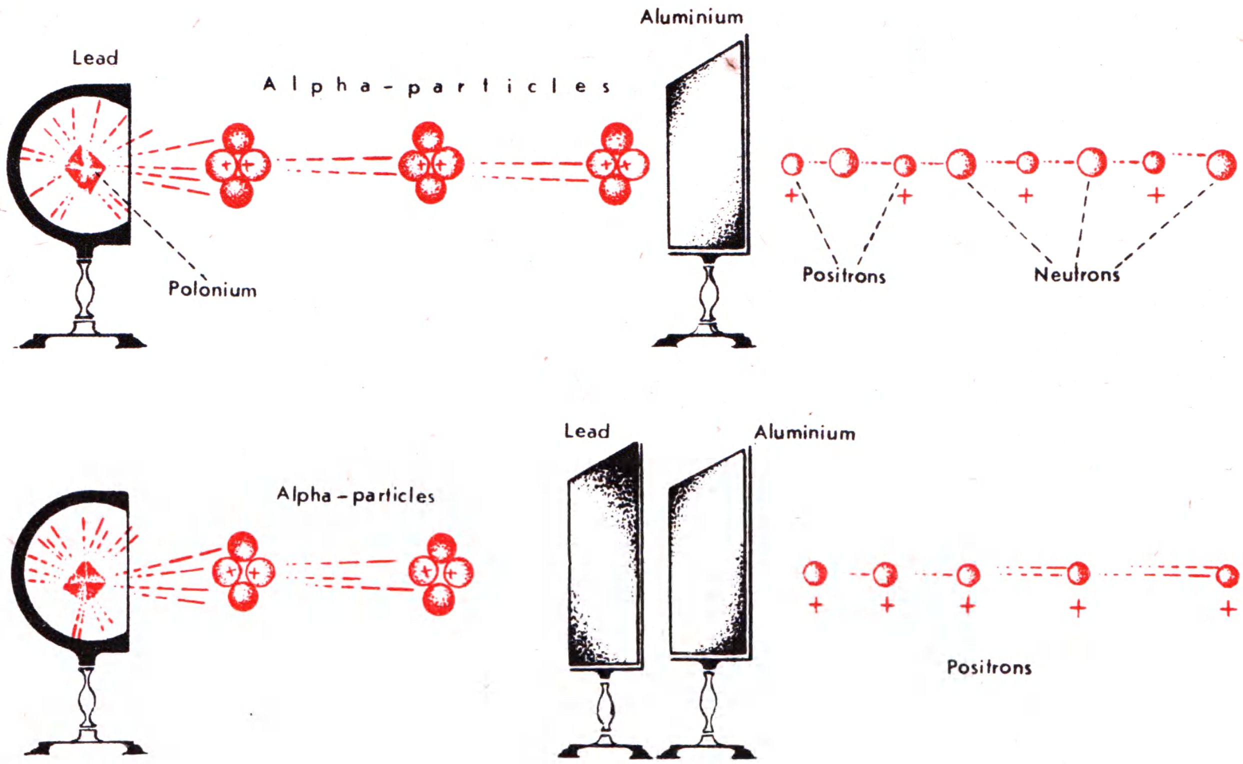
Wishing to investigate in greater detail the composition of the resulting secondary radiation, Irene and Fréderic Joliot-Curie used a Wilson cloud chamber. One day, having directed a beam of neutrons from a bombarded piece of aluminium through the chamber, just as in the Bothe and Becker experiments, they detected a large number of tracks left by light, positively charged particles. These were the tracks of positrons, positive electrons, discovered by the American H. L. Anderson three years before, particles that were similar to electrons in all respects, except in the sign of the charge.



Reproduction of the first photograph of the track left in a Wilson cloud chamber by a positron, a particle differing from an electron only in the sign of its charge

But the most interesting discovery lay ahead. When the source of alpha-particles was removed, i.e. after the scientists ceased to bombard the aluminium plate, the neutrons disappeared, as was expected. But the emission of the positrons continued, only at a gradually decreasing rate. Every 2.5 minutes the number of the positrons emitted fell by a factor of two.

No known natural radioactive element possessed such a half-life. Moreover, the new phenomenon differed from natural radioactivity in that the emission of positrons from the aluminium



Schematic representation of the experiment that led Irene and Fréderic Joliot-Curie to the discovery of artificial radioactivity. Aluminium, irradiated by alpha-particles, continues to emit positrons even after a lead screen, that completely stops alpha-particles, is placed between the aluminium target and the source of alpha-particles

plate began again as soon as it was irradiated with alpha-particles, all of which indicated that the alpha-particles were forming some new element in the aluminium, whose radioactive decay was accompanied with the emission of positrons.

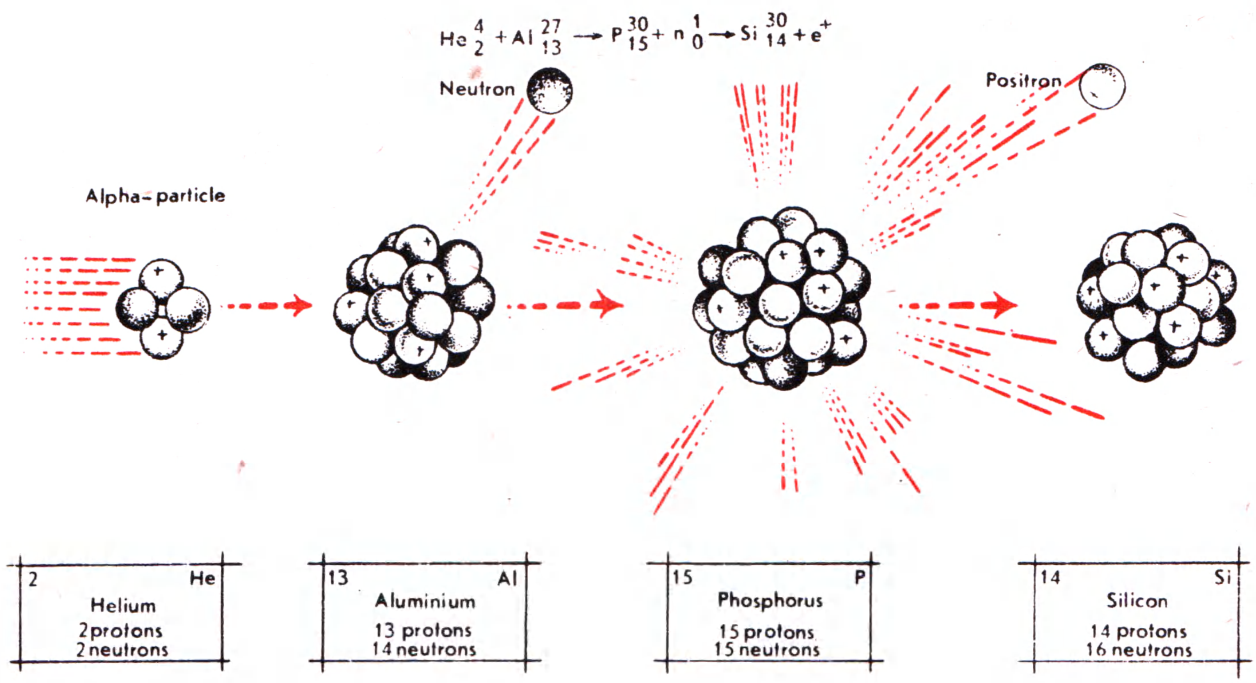
More thorough investigation of this reaction made it possible to conclude that the aluminium nucleus ($_{13}Al^{27}$), having captured an irradiating alpha-particle ($_2He^4$), ejects a neutron and becomes an isotope of phosphorus with an atomic weight of 30 ($_{15}P^{30}$). Stable isotopes of phosphorus with such an atomic weight do not, however, occur in nature, so it obviously must disintegrate. During its decay the isotope emits a positron, which can happen if one of the protons in the phosphorus nucleus is replaced by a neutron. The unusual phosphorus is then transformed into silicon ($_{14}Si^{30}$) the nuclear charge of which is one unit smaller. In other words, during the new reaction the nucleus lost a positive electric charge but preserved its mass. The process may be written thus:

$$_2H^1 + {}_{13}Al^{27} \rightarrow {}_{15}P^{30} + {}_0n^1$$

The radioactive phosphorus formed disintegrates and, having emitted a positron, becomes silicon:

$$_{15}P^{30} \rightarrow {}_{14}Si^{30} + e^+$$

The new phenomenon added several more difficult riddles to the heap of unsolved puzzles. Where did the positron come from? What caused a proton to disappear? Why was it replaced by a neutron? And so on. An answer could



When aluminium is bombarded with alpha-particles, its atoms first turn into radioactive phosphorus, then into silicon

only be obtained by more experiments. It is not surprising, therefore, that soon after the discovery was announced scientists in various countries began to use nuclear particles to bombard literally every chemical element in the Table. And they found that almost all of them could form new radioactive isotopes. The number of artificial radioactive sources soon rose to 1 000, and every year more and more new ones were discovered.

Another Mistake!

In the 1930s a young and very gifted Italian physicist, Enrico Fermi, began working at the University of Rome. Intrigued by the sensational discovery of artificial radioactivity by Irene and Frédéric Joliot-Curie, Fermi and his coworkers studied what happened when the atoms of various elements were bombarded with neutrons, using a radium-beryllium source as their atomic 'gun'.

In a short time they had bombarded the atoms of every element in the Periodic Table by means of their quite convenient and simple source of neutrons. And as was to be expected, they often obtained artificial radioactive substances.

At last it was the turn of uranium. Being a very inquisitive and speculative man, Fermi supposed that uranium, after having captured one or more of his neutron projectiles, would be transmuted into a heavier element still, one that had not yet been discovered in naturre He made the experiment first in 1934. On being exposed to neutron bombardment, the uranium became even more radioactive than before, and in addition, four kinds of radioactive nucleus were discovered in it, with different half-lives.

This gave Fermi grounds for concluding that he had discovered four new superheavy elements (such elements later came to be called transuranic, because they came after uranium in the periodic system).

There is no need here to describe the excitement of scientists in all countries as they began to try and separate and study these new transuranic elements, endlessly repeating Fermi's experiments. The results they obtained seemed on the whole to agree, but things began to happen that were inexplicable and troubled them. First, there was the ease with which the number of newly discovered types of radioactivity continued to grow. And then despite their ingenuity and efforts, none of the researchers succeeded in separating the newly created elements from the mass of uranium.

The search continued for five years. Then in 1939 something quite unexpected happened. One of the new elements, discovered by the German chemists O. Hahn and F. Strassmann in uranium bombarded by neutrons (according to Fermi it should have an atomic number of 93, 94, 95, 96, or even 97), turned out to be barium, which is located in the middle of the Periodic Table and has an atomic number of only 56; another was lanthanum-57.

Scientists were understandably confused. In no circumstances could a neutron, having hit the nucleus of element 92 and become embedded in it, turn the element into barium or lanthanum, since they were almost half as light as uranium. The experiment was repeated time and again, and each time gave the same result—the formation of barium and lanthanum from the bombarded uranium. And the more the scientists worked, the more it seemed to them that their results contradicted the whole previous experience of nuclear physics.

It was not until the autumn of 1939 that the Austrian physicists Lise Meitner and her nephew Otto Frisch, who were then working in Denmark at the University of Copenhagen where they had fled from fascist persecution in Germany, explained what it was that happened when uranium was bombarded with neutrons.

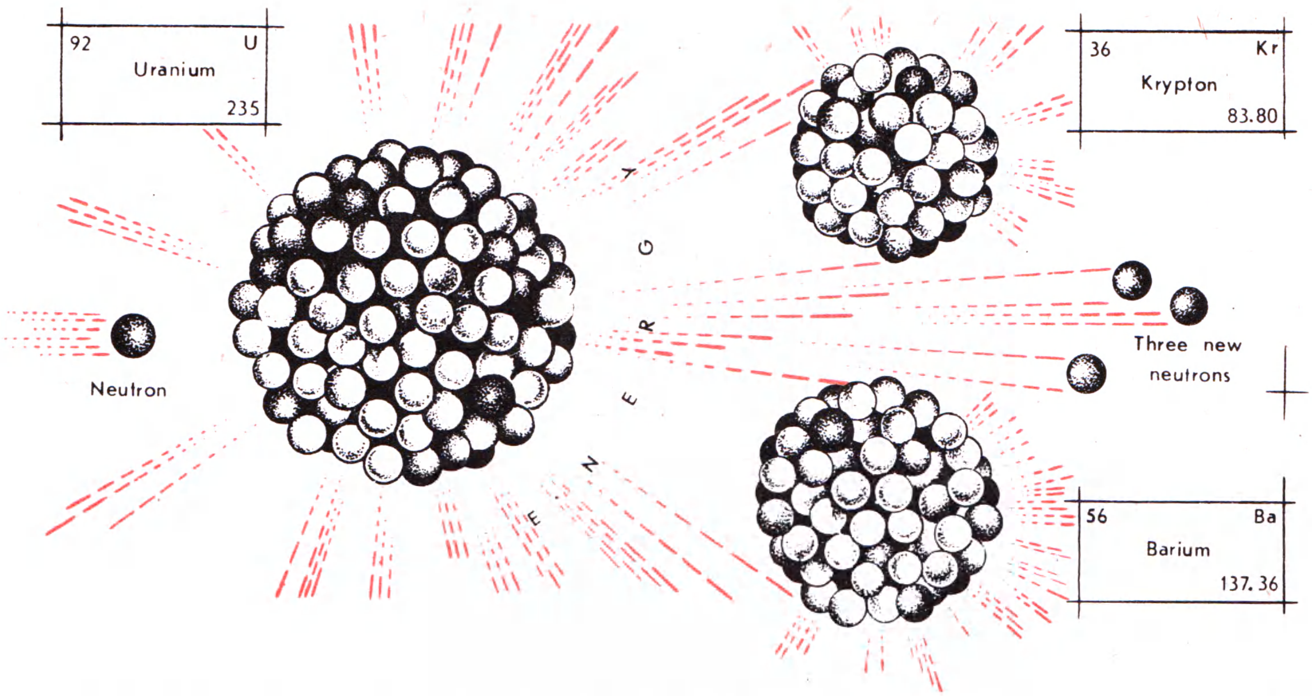
By means of quite sophisticated experiments they showed that two particles with approximately half the mass of uranium were formed during this interaction and flew off in different directions. The tracks were clearly and distinctly to be seen on photographs of a Wilson cloud chamber taken later.

There was no room for doubt. Neutrons split the nucleus of uranium into two parts, at the same time releasing enormous energy. Miss Meitner and Frisch explained the phenomenon in this way. The larger and more massive the nucleus of an atom, the less stable it is. And when a foreign particle of some kind hits such an unstable nucleus it imparts additional energy to the latter and sets it into violent motion. The nucleus becomes excited and may even split in certain definite circumstances. There was nothing to wonder at that the uranium nucleus, being as unstable as it was, should break up suddenly after capturing a neutron, instead of ejecting one or more particles, as happened with lighter elements. This nuclear reaction came to be called atomic fission.

Fission resulted in the appearance of two fragments, nuclei of elements with atomic weights between 80 and 160, bromine and lanthanum, for example, or barium and krypton, etc. The fragments proved to be highly radioactive, and only became stable after several successive disintegrations and the emission of beta-particles.

The scattered fragments possessed high kinetic energies, which proved to be hundreds of times greater than those of the partial splitting of nuclei by alpha-particles and protons.

Once the fission reaction had been discovered, all experiments with other elements were almost completely aban-



Nuclear fission of uranium results in the formation of two atomic nuclei of quite different elements, e.g. krypton and barium

doned, as if on command, and atomic physicists directed massed 'artillery fire' on a narrow sector of the front of nuclear physics, on the atom of uranium, which had proved so unstable.

With ordinary artillery all the efforts of scientists, inventors, and ordnance designers have been directed toward obtaining great muzzle velocity with maximum weight of the projectile. The higher the muzzle velocity, the greater is the kinetic energy of the projectile and the greater the destructive power of a hit.

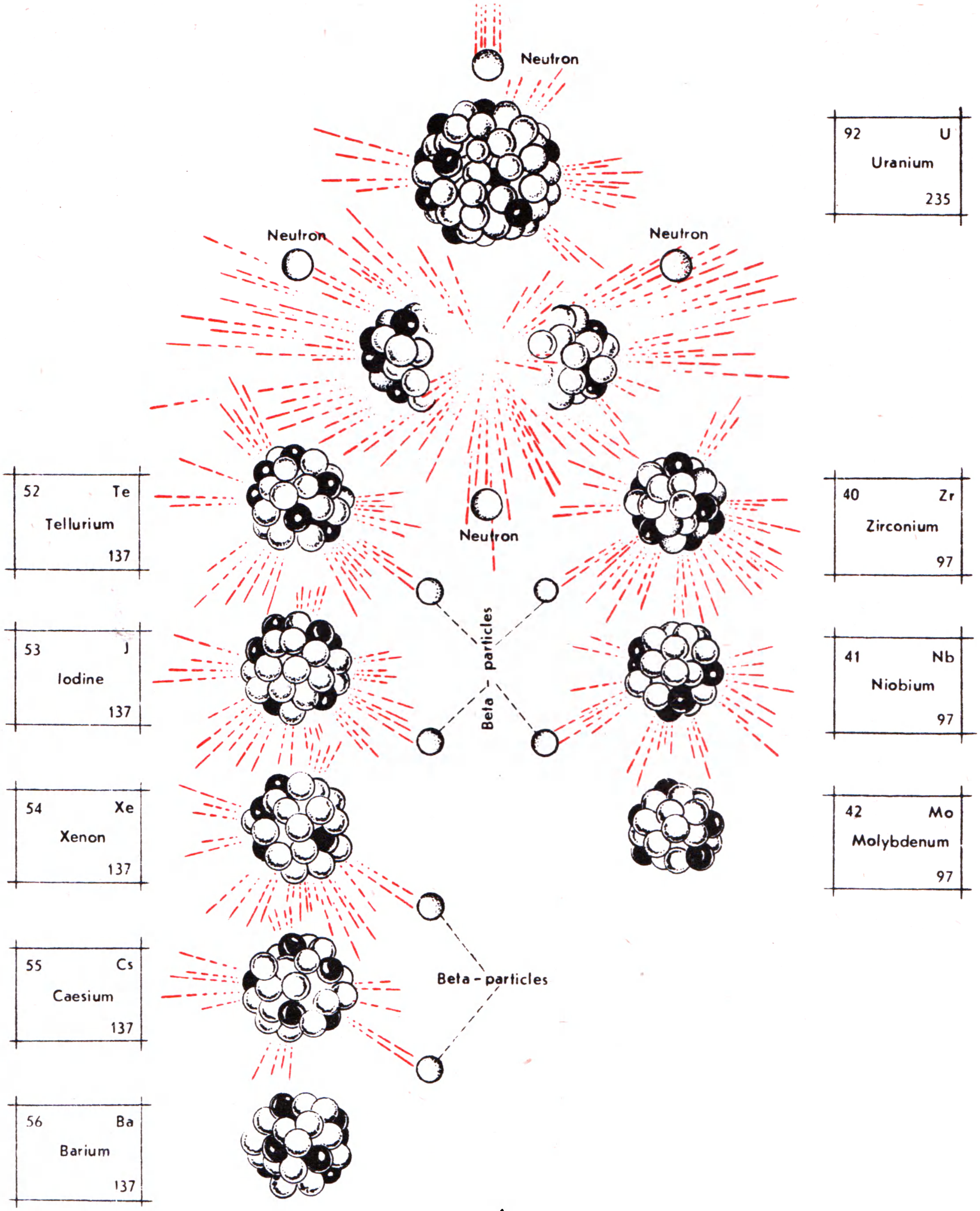
In the same way, scientists bombarding atomic nuclei also tried to get 'projectiles' that would be as massive as possible and possess the highest possible velocity. The ideal was to impart a velocity to an alpha-particle or proton close to the speed of light.

Then an obvious exception to the accepted rule led to a quite unexpected but pleasing result. Neutrons, which possessed relatively low kinetic energy, were found to be superbly capable of causing fission of uranium.

What made this new phenomenon of nuclear fission so remarkable?

First of all, the fact that it is accompanied with the release of extraordinarily great energy. Calculations, and later practical measurements, showed that each time a uranium nucleus split into two halves, about 200 MeV were released.

But something else was even more important. This was the fact that while the nuclei of any pair of fission products—xenon and zirconium, bromine and lanthanum, etc.—contained between 129 and 140 neutrons, the uranium nucleus itself contained 143-146. So several neutrons, two or three on average, that had previously remained comparatively quitely 'in their places' in the uranium nucleus, proved to be superfluous for the daughter atoms; and having a surplus of neutrons, these atoms either got rid of them at once



What happens to the fission products of uranium nucleus

or possessed what is called *neutron radioactivity* and ejected them some time later.

And just like the uranium fission products themselves, these neutrons flew off with enormous energies of the order of 1.0 to 1.5 MeV.

It is important to recall here that each of these free neutrons was also able in turn to cause the fission of a uranium nucleus. We still have much to say about the peculiarities of neutrons, but it would be well first to look more closely at what happened to the uranium. For it contains several isotopes. What do neutrons do to them? And what special properties must these neutrons have?

The Family of Uranium Isotopes

In 1935, four years before fission was discovered, an event occurred in a laboratory of the University of Chicago that almost passed unnoticed, but that was nevertheless of the utmost importance for atomic physics.

A chemist, Prof. Arthur Dempster, from Canada, was working there. His speciality was study of the various elements by means of a very intricate instrument, the mass spectrograph. Employing this instrument scientists had shown that the atoms of many natural elements with identical chemical properties nevertheless had different atomic weights, or were isotopes (with which we are already familiar).

One day, as he was investigating the spectrum of pure uranium, Professor Dempster unexpectedly noticed on the plate alongside the broad band usually given by uranium-238, another, scarcely visible band. This turned out to be the trace of a very rare isotope, uranium-235. A little later an even rarer isotope, uranium-234, was detected. Very delicate measurements showed that pure natural uranium contained 99.28 per cent of uranium-238, 0.714 per cent of uranium-235, and a mere 0.006 per cent of uranium-234.

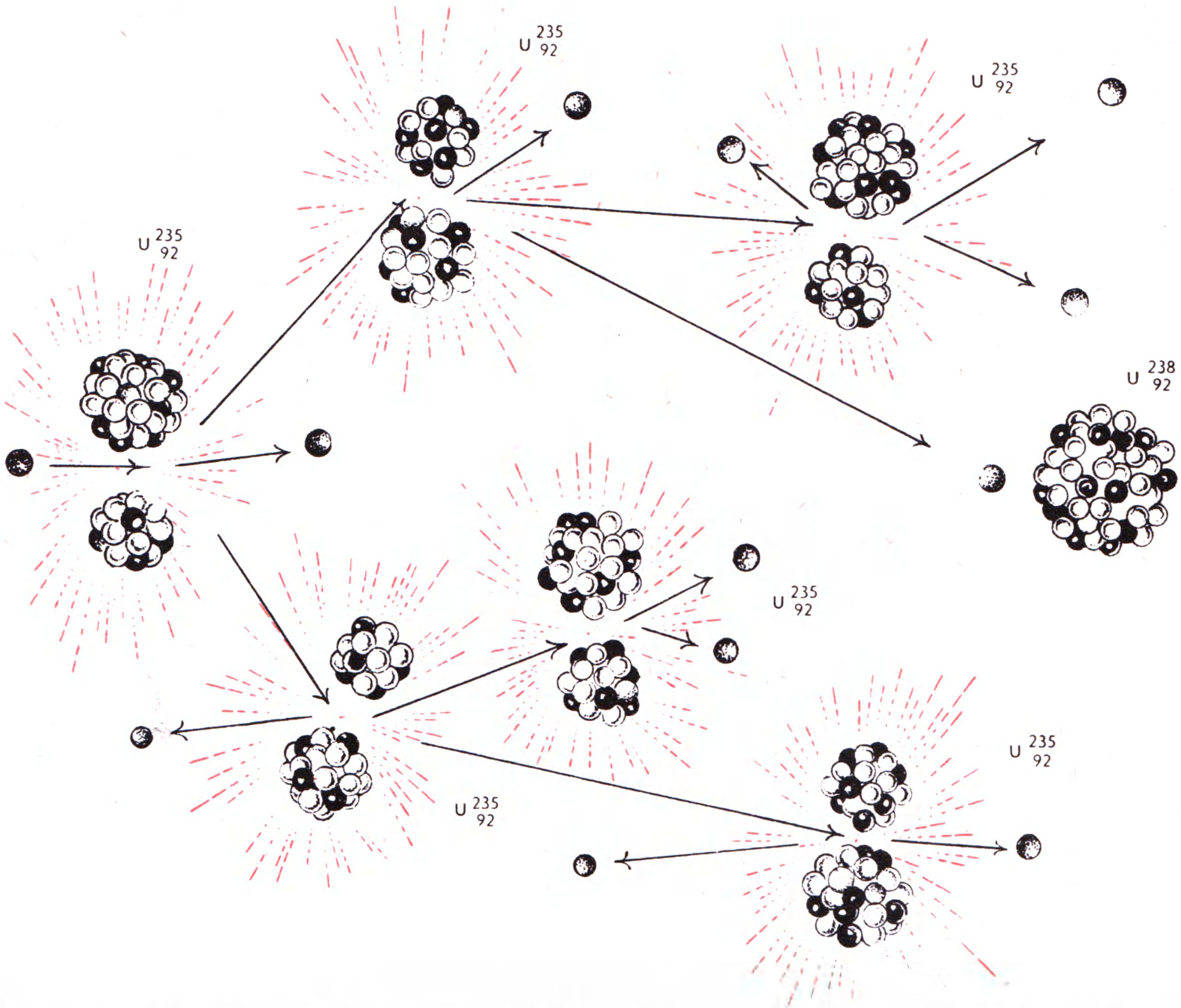
It was not for five years after this apparently not very notable event that scientists succeeded in establishing that neutrons of any energy caused very intensive fission only of the nucleus of uranium-235 (of which there is only 0.7 per cent in natural uranium); and the lower the energy of the neutrons the more intensive was the fission. So-called thermal neutrons with an energy of the order of 0.03 MeV were especially good. The main isotope, uranium-238, was split only by very fast neutrons with an energy of the order of one or two million electron-volts.

It is very characteristic of modern physics and significant that soon after the discovery of the isotopes of uranium, the famous Danish physicist Niels Bohr and a young American physicist John Wheeler, of Princeton University, theoretically predicted the possibility of the fission of the lightest isotope uranium-235 through the action of slow, thermal neutrons.

The Cherished Goal Reached

In the whole chain of discoveries connected with the nuclear fission of uranium, perhaps the most striking and important was the interesting fact that the uranium nucleus also lost two or three free neutrons unconnected with the nuclei of the main fragments (as we have already mentioned).

Bearing in mind the capacity of neutrons to split the nuclei of uranium into two or three fragments it could now be supposed, albeit theoretically, that each of the three neutrons ejected from a split nucleus, given suitable and favourable conditions, could hit a neighbouring atom and split it as well. And



To initiate the avalanche-like development of a chain reaction of nuclear fission of uranium-235, only one neutron is required

that atom, in splitting, would fire a new salvo of three neutrons which, in turn, would cause fission in three neighbouring uranium nuclei, and so on. In consequence one could expect a chain reaction of nuclear fission in uranium, growing at breakneck speed (3, 9, 27, 81, 243, 729, etc.).

And even if only one at most of the first-generation neutrons caused a secondary fission reaction, out of the two or three (on average 2.5-2.7) that proved 'too much', and at least one neutron of the second generation did the same, and so on, a self-sustaining chain reaction would set in, a reaction that did not need any outside source of neutrons.

When scientists first succeeded in detecting the fission of uranium induced by neutrons, the reaction naturally was not a branching or simply self-sustaining chain reaction, for when the external neutron source was removed fission ceased at once. The fissile material, as Niels Bohr had indicated, could

only be uranium-235; and the neutrons given off by its fission were very quickly decelerated by collisions with the nuclei of neighbouring atoms of the main isotope, uranium-238, in which they could not induce fission. But if there were sufficient uranium-235 around the point where fission began, then such successively increasing fissions would produce an instantaneous explosion of such fantastic force that the energy it released would be millions of times greater than that produced by the most powerful explosive made by man.

The conclusion was so shattering that it literally knocked the wind out of the scientists concerned with these problems.

A little while later, on 30 April 1939, a paragraph along the following line appeared in the press: Dr. Niels Bohr of Copenhagen has declared that, by bombarding the pure isotope uranium-235 with slow neutrons, a chain reaction or atomic explosion can be induced, the force of which would be so vast that it would blow the laboratory to smithereens and destroy everything around for a radius of several miles.

All further publication of articles and information on this theme suddenly ceased all over the world.

Scientists had stumbled on the path that seemed to lead directly to the goal. The long silence was deepened by the outbreak of World War II, ... and then came 16 July 1945.

That day, 16 July 1945, was the date of an event of exceptional importance in the history of mankind. That day, before the eyes of scientists, engineers, technicians, soldiers, and representatives of the civil authorities of the USA, watching with bated breath, the first atomic bomb was exploded at 5.30 a.m. in the desert near Alamogardo in the State of New Mexico.

In a small amount of fissile material, uranium-235, an instantaneous chain reaction was induced, releasing the tremendous energy that had been locked up inside the atomic nucleus since the beginning of time.


ЛЕНИН
LENIN

Chapter Six

ABOUT 'HORRIBLE THEORY'

Almost Back at the Beginning

So far we have been setting out only the facts that, gradually piling up and growing like a snowball, led scientists to understanding of many of the fine features of the structure of matter and enabled them to discover the tremendous reserves of energy locked away in the atom.

The nuclei of the chemical elements, which had previously seemed the passive and simplest 'bricks' from which the world around us is built, now turned out to be composed of still smaller particles that moved at enormous velocities and possessed great energy. Many of them were brought together and held together, despite gigantic forces of mutual repulsion, by even more tremendous intranuclear forces like the strength of a colossal spring.

And although the origin and nature of these unusual, previously unknown forces had not been elucidated with any exactness or certainty, scientists had nevertheless not only made contact with them but also discovered means of 'letting them loose'.

It would be wrong to think that all this research had been done blindly, without a clue, without theory. Quite the contrary. It was deep theoretical searching that each time had prompted scientists what direction to take and had explained why many of the amazing and unusual processes discovered in the microworld developed (or should develop) in the way they did and not otherwise.

Any theory or idea, every conception of nature, is based, in the final analysis, on experimental data, on what actually happens in nature.

And practice and experiment, in turn, are the nutrient medium on which scientific hypotheses and theories grow and develop, and sometimes wither and die.

Of course, when scientists came across incomprehensible phenomena, sometimes contradicting common sense, theory occasionally led them into a labyrinth of empty pure fantasy, especially when practice had brought theory to a dead end (as quite often happened, by the way). But it was scientific practice that forced the theory to perfect itself, and in the long run it was practice that convincingly refuted outlived or too hasty and unsubstantiated theories, and forced scientists to throw them aside.

And no matter how much we would like to continue using habitual ideas, images, and comparisons to explain the events that led up to man's first advances in liberating atomic energy, we must, however, touch on certain problems of theory in order to get a proper understanding and true conception of the physical processes going on in the world of the atomic nucleus, and in that connection we must go back a little, and return to what we know about particles, and mass, waves, and electric charges, and light.

Particle-Waves and Wave-Particles

The discovery of radioactivity was noteworthy because, among other things, it gave scientists so many new data and facts that they could already create more complete and exact theories of the structure of matter, and in particular to explain the existence of immense energy hidden away in the atomic nucleus. The existence of that energy was confirmed by all experiments, without exception, but could not be explained by the old, so-called classical, physics.

Hitherto, for example, it had been thought that energy could be transferred in two quite different ways, either by the movement of a particle or corpuscle or by means of wave oscillations excited in a definite material medium.

At first radioactive radiation seemed to confirm this. Alpha-particles proved to be positively charged nuclei of helium and beta-rays electrons, negatively charged particles travelling at very high velocity. Only gamma-rays proved to be rays, that is, electromagnetic waves of very short length, even shorter than X-rays.

But as physical research developed, it became obvious that it was becoming more and more difficult with every year to continue to classify radiation in the old way as particles and waves. In some experiments electromagnetic waves behaved like particles, but in others they had clearly expressed wave properties.

It made physicists speak of dualism, of the dual nature of particles and waves.

In the concepts of classical physics, a particle is a material body occupying a definite volume of space and possessing inertia, that is to say, the property of resisting, as it were, any effort to put it into motion or to alter its speed or direction when in motion. The mass of a particle was considered to be the measure of inertia, and the unit of mass in the system of physical measurements is the gramme.

One of the normal forms of energy is that of motion or kinetic energy, which serves as the measure of the force that must be applied to a body either to set it in motion or to stop it. The higher the speed of a body, the greater is its kinetic energy.

According to the laws of classical mechanics, any moving body possesses a kinetic energy equal to half the product of its mass and square of its velocity:

$$E_k = \frac{mv^2}{2},$$

where m is the mass and v the velocity of the moving body or particle.

By very delicate and precise experiments scientists were able first to deter-

mine the charge of such a light particle as the electron and then its mass which proved to be 9.11×10^{-28} gram. But it turned out to be impossible to determine its exact size, or its position in the atom at any moment of time.

The point is that in the world of such minute but rapidly moving particles, any attempt to discover or measure them inevitably involves an interaction between the particle and the measuring instrument invading this world. By instrument here we mean any physical method of external action: device, instrument, substance, light, heat, electrical or magnetic field, etc.

As a result of the invasion the particle changes its properties (speed, direction, energy), sometimes quite drastically, and the instrument will indicate not the actual physical properties it possessed before the experiment, but those resulting from its interaction with the instrument itself.

To be made to judge the true properties of particles, then, it is necessary to take their interaction with the measuring instrument into account, no matter how complicated and varied that interaction may be. And the more accurately the interaction is established and calculated and the more often that is done, the more reliable our knowledge of the true properties of particles will be. But that is only a very arbitrary assumption, that enables us to avoid dangerous impasses. The fact is that the electric charge, and consequently its carrier, the electron, remains a puzzle to physicists to this day. If one imagines an electron (and this applies not only to the electron, but to any other charged particle) as a finite system concentrated within the limits of an arbitrarily small region of space, it is natural to consider that its charge is also distributed over this space. But if that is the case, why do the various sectors of the charge, of which the particle is composed, not repulse one another. Why do they not cause the particle to split up into smaller parts and these to split up into even smaller fragments?

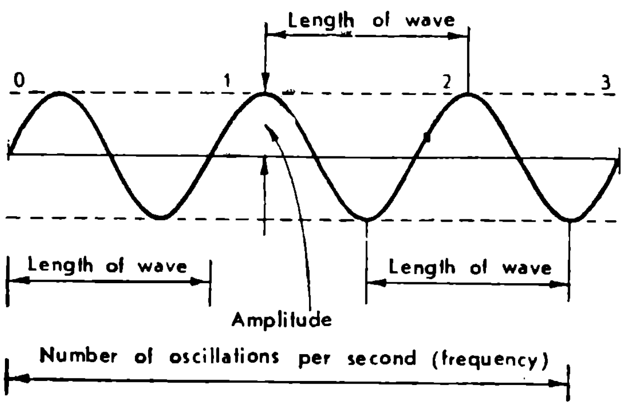
Scientists studying the physics of microparticles were driven willy-nilly to assign average, approximate dimensions of some sort to particles, and to guess or predict their position or properties from the results of a great number of external invasions, i.e. attempts to make measurements. Each invasion found the particle investigated in some other phase of its true position or motion. Taken all together, these invasions gave only a rough idea of the true properties of particles.

Therefore, in those cases where it does not lead to deeper contradiction, the electron may be considered a material point, as in geometry, that has no dimensions.

Paradoxes of Wave Motion

When a moving particle collides with any immovable or displacable obstacle, it imparts all or part of its kinetic energy to this obstacle. Our every-day experience makes it quite easy to understand this process. It is considerably more difficult to visualize the transfer of energy in wave motion.

The simplest kind of wave motion is that of a wave on the surface of water. It seems to us, for instance, that when a stone is thrown into a pond water rushes at great speed in every direction from the centre of agitation. The water, however, does not overflow the banks of the pond, nor does it leave a gaping hole at the spot where the stone fell. Chips or corks floating on its surface are not pushed to the bank by the waves, but merely begin to bob up and down, remaining where they were. The



The relation between the number of oscillations per second of a wave and its length

medium transmitting the waves is not displaced together with them but remains in place. Only the disturbance is displaced.

Wave motion also has its peculiarities and laws. The one of greatest importance is its frequency, that is, the number of oscillations per minute (f). Frequency does not characterize the medium in which a wave is propagated, but only the source of disturbance. In all cases the frequency of a wave passing through any medium whatever can only be the same as that of the source of oscillation. But its velocity of propagation does depend on the properties of the medium, and is quite independent of the source of the wave. It is the medium that determines the velocity with which waves of this kind are propagated in it.

With a source frequency of f and velocity of propagation of v, the length of a wave λ is

$$\lambda = \frac{f}{v}$$

Another characteristic of a wave is its amplitude, which determines the energy carried by it at a given velocity of propagation. By the amplitude of a wave we mean the distance between the undisturbed level of the medium, for instance, the surface of the water in the pond, to the point of maximum displacement, i.e. the height of the wave. Think of the innocent ripples on the surface of a pond, and of the might of the surf during a gale at sea.

Waves are propagated in all directions (in circles, spheres) from the source of disturbance, and any circle or sphere the points of which undergo equal displacement, is known as a wave front.

There are a whole number of phenomena connected with wave motion that are common for all waves.

When a wave, or a ray (if we are dealing with light), falls on a flat surface the wave or ray is reflected, and the angle of reflection is equal to the angle of incidence. But please note: reflection can take place without wave motion. When a steel ball hits a flat plate, its angle of reflection, too, is equal to the angle of incidence.

When a wave passes from one medium into another that has a different velocity of propagation, the direction of the wave's movement is altered (e.g. refraction of a beam of light occurs).

When two waves of equal length and amplitude, but of opposite phase, are superimposed on one another in such a way that the crest of one coincides with the trough of the other, the two waves cancel each other out. But when their crests and troughs coincide, the waves are amplified and their amplitude is doubled. This phenomenon is known as wave interference, and is only characteristic of wave motion.

Wave motion also involves certain essential distinctions and fine points; for example, waves may differ in the direction in which they displace particles of the medium in which they propagate (air, water, solids, etc.).

With sound waves, molecules of air oscillate along the direction of propagation of the waves and the air is alter-

nately compressed and expanded. Such waves are called longitudinal. A stone dropped into water excites a transverse wave; in it the molecules of water oscillate in a direction perpendicular to the movement of the wave.

In addition to transverse waves, longitudinal sound waves can also arise in water.

How Electromagnetic Waves are Formed

We know that bodies charged with electricity of opposite sign attract each other, while those charged with electricity of like sign, repel one another.

Because this property of charged bodies was so illustrative and easily checked by experiment, it became so habitual and self-evident that no one, it seems, had doubts about it.

But it is a most important fact about the interaction of electric charges that when the distance between them is changed through the movement or displacement of one of them, the second charge reacts to the change of distance not at the moment the first charge is displaced, but only after lapse of the time required for light to travel the distance between the two charges.

The famous British scientist James Maxwell suggested that an electromagnetic field arises around moving charges, and is propagated in all directions with the speed of light, in the form of electromagnetic waves. He demonstrated that visible light was a very narrow zone of electromagnetic waves of extremely high frequency, i.e. that there was a link between electrical and light phenomena.

Like light, radiowaves, invisible ultraviolet and infra-red light, X-rays and the gamma-rays emitted by radioactive substances, are all electromagnetic oscillations.

What is Light?

In 1899 the distinguished Russian physicist, Prof. P. N. Lebedev of the Moscow University, conducted a series of brilliant experiments by which he proved that light exerted pressure on all the matter on which it fell, and accurately measured the magnitude of this pressure.

A thin and very light metal plate put in the path of a beam of light is displaced a little by its pressure. On a bright day the pressure exerted by light on a surface one metre square is 0.00047 gram.

This experiment, which led to the indisputable conclusion that a flux of light had mass, once more brilliantly confirmed the correctness of the materialist outlook on the nature of various physical phenomena so that it was not strange that reactionary philosophers gave this conclusion a hostile reception.

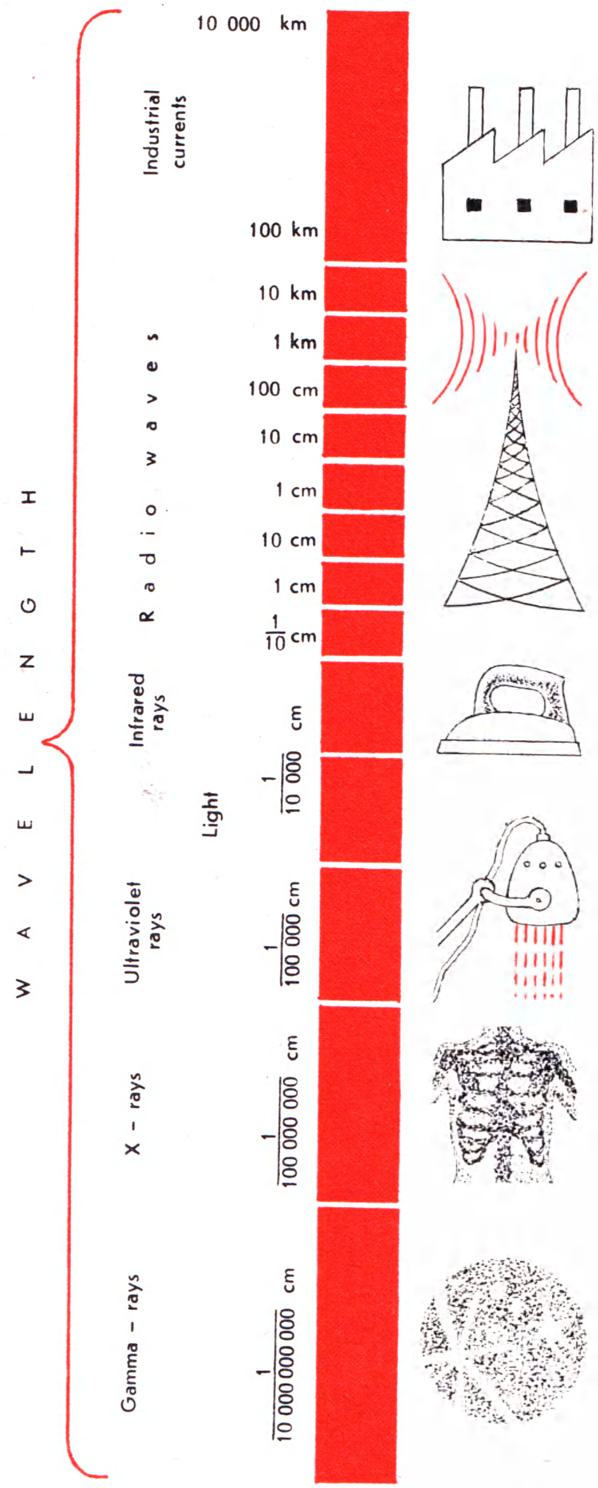
Of course, the concepts 'matter' and 'mass' are by no means identical; consequently, an object need not be considered as material simply because it possesses the properties of mass.

Lebedev's experiment gave another new and important scientific proof of the continuity of matter and motion in the form of the quite visible and natural link existing between the mass and energy of light. It enabled scientists to draw the only correct conclusion, that light is a form of matter in motion, i.e. that the whole material world, matter in motion, exists in two principal, mutually related, forms—as of moving particles of matter, and as light.

It was one thing, however, to come to the conclusion that light was a form of matter in motion, and quite another to be able to prove it experimentally.

Photons, the Particles of Light

Although the behaviour of light, X-rays, and gamma-rays in normal conditions



The place occupied by radio waves, X-rays, and gamma-rays among the electromagnetic oscillations encountered in nature

could be taken as convincing evidence of their wave nature, a whole number of phenomena had nevertheless been observed that could not in any way be explained by the theory of wave motion. They could only be explained by assuming that waves, at least when they interacted with matter, had the properties of discrete particles (i.e. of particles of a certain finite magnitude).

One of these properties was connected with what is called the photoelectric effect, which consists essentially in the following: a metal plate exposed to ultraviolet light or X-rays begins to emit electrons, whose kinetic energy depends on the frequency of the incident rays, but is independent of the intensity of the incident light. The intensity of the incident light only effects the number of electrons emitted per unit of time.

Another phenomenon of the same order is Compton's famous experiment, which consisted in the following: a narrow beam of X-rays is directed at a piece of coal and is scattered by it in all directions. Around the coal is positioned an X-ray spectrograph, an apparatus to detect the X-rays reflected from the coal. According to the wave theory, the energy of the X-rays should be transmitted to the electrons of the atoms of carbon, turning them into new centres of excitation from which rays would be emitted as secondary waves. The process could seemingly only change the direction of the scattered rays, but not their wavelength. Measurements, however, showed that the wavelength of the secondary scattered rays only coincided with that of the primary rays when reflected at an angle of 0°, for all other directions or angles of reflection the wavelength increased.

If the incident radiation actually consisted only of rays it would be impossible to explain the observed pheno-

menon. But Compton explained the interaction of X-rays with electrons by the X-rays not solely behaving as rays but, in a certain sense, also behaving as particles, each possessing a definite energy and momentum. In colliding with an electron at different angles, X-rays imparted different amounts of energy to it—more at small angles, and less at large angles.

It was thus established that the dual wave particle property can be attributed with equal justification to X-rays and gamma-rays as well as to light.

In 1901 the famous German physicist Prof. Max Planck put forward a theory that energy is released and absorbed in the course of physical transformations and the interaction of the atoms of a substance, not in a continuous unbroken flux, but as though concentrated in small amounts. In other words, Planck spoke of the possible existence of a peculiar atom of energy.

In 1905 the renowned German physicist Albert Einstein established that light could only be absorbed in definite portions or parcels, and that the photoelectric effect could best be explained by assuming that light waves were absorbed in packets of a definite size.

Hence, light is absorbed by various substances, and is emitted by the atoms of an excited substance (e.g. heated to luminescence), in strictly determined portions. These portions later received the name of quanta.

Planck considered the unit of energy of a quantum to be a magnitude derive from the formula

$$E = h\nu$$

where E is the energy of a quantum in ergs; ν is the frequency of oscillation of the source of radiation; and h is a constant, equal to 6.62×10^{-27} erg·sec (Planck's constant).

It follows from this simple formula that the higher the frequency of electro-

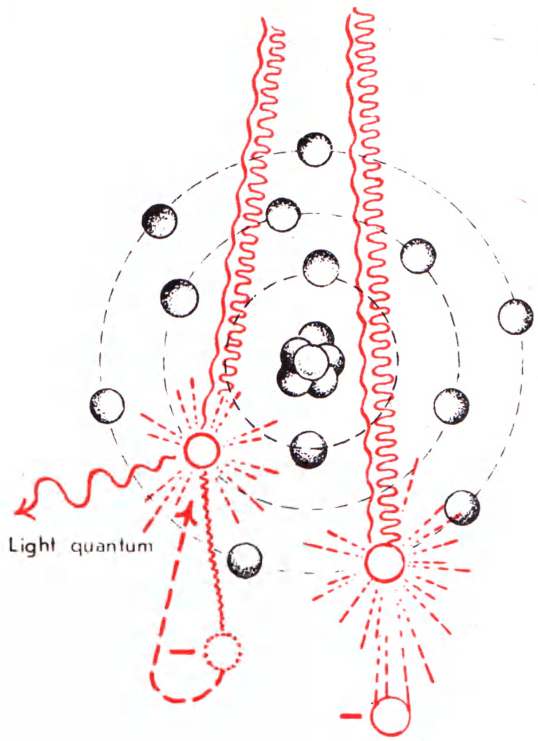
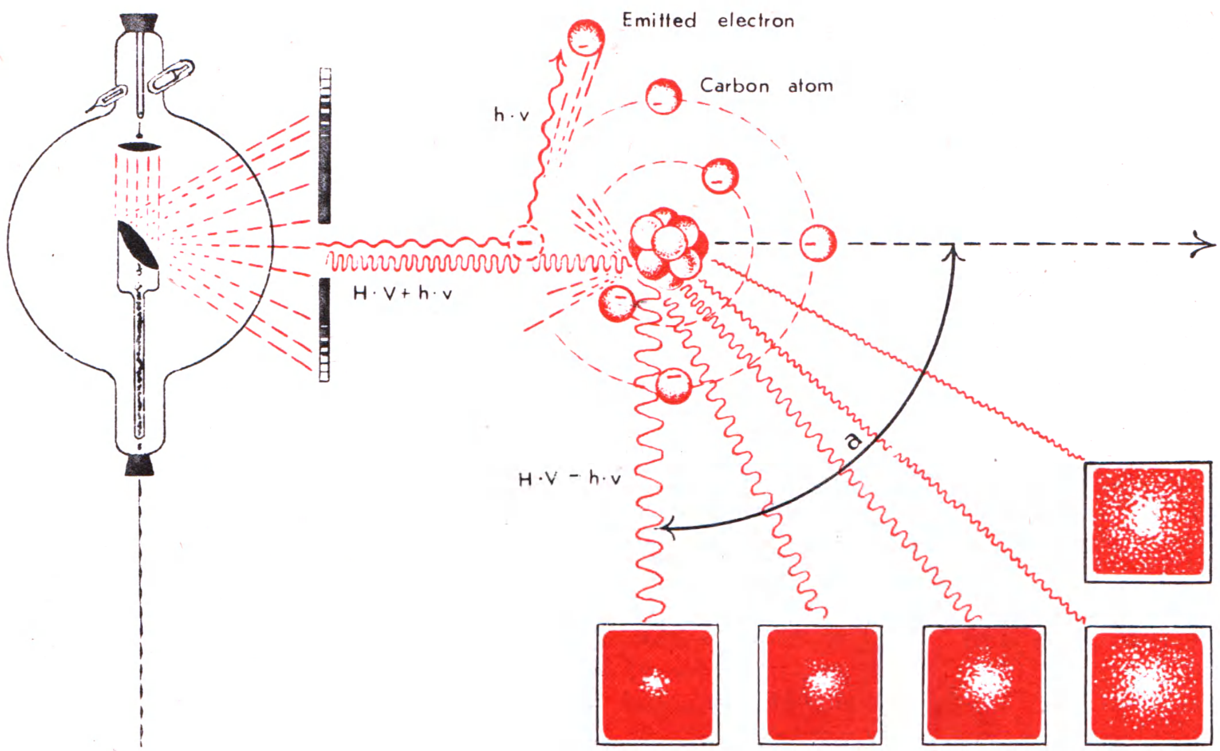


Diagram explaining the photo-electric effect of light (knocking out of electrons). A photon, possessing a certain energy ($\Sigma = h\nu$), expends its whole energy, or a strictly multiple fraction of it, in performing the work required to knock an electron out of an atom. The electron knocked out acquires a kinetic energy equal to the difference in the energy of the foreign quantum and the energy spent to move the knocked out electron ($\Sigma - E$). But if the energy carried by the foreign quantum Σ is inferior to E, the electron will not be knocked out of the atom and no photo-effect is observed



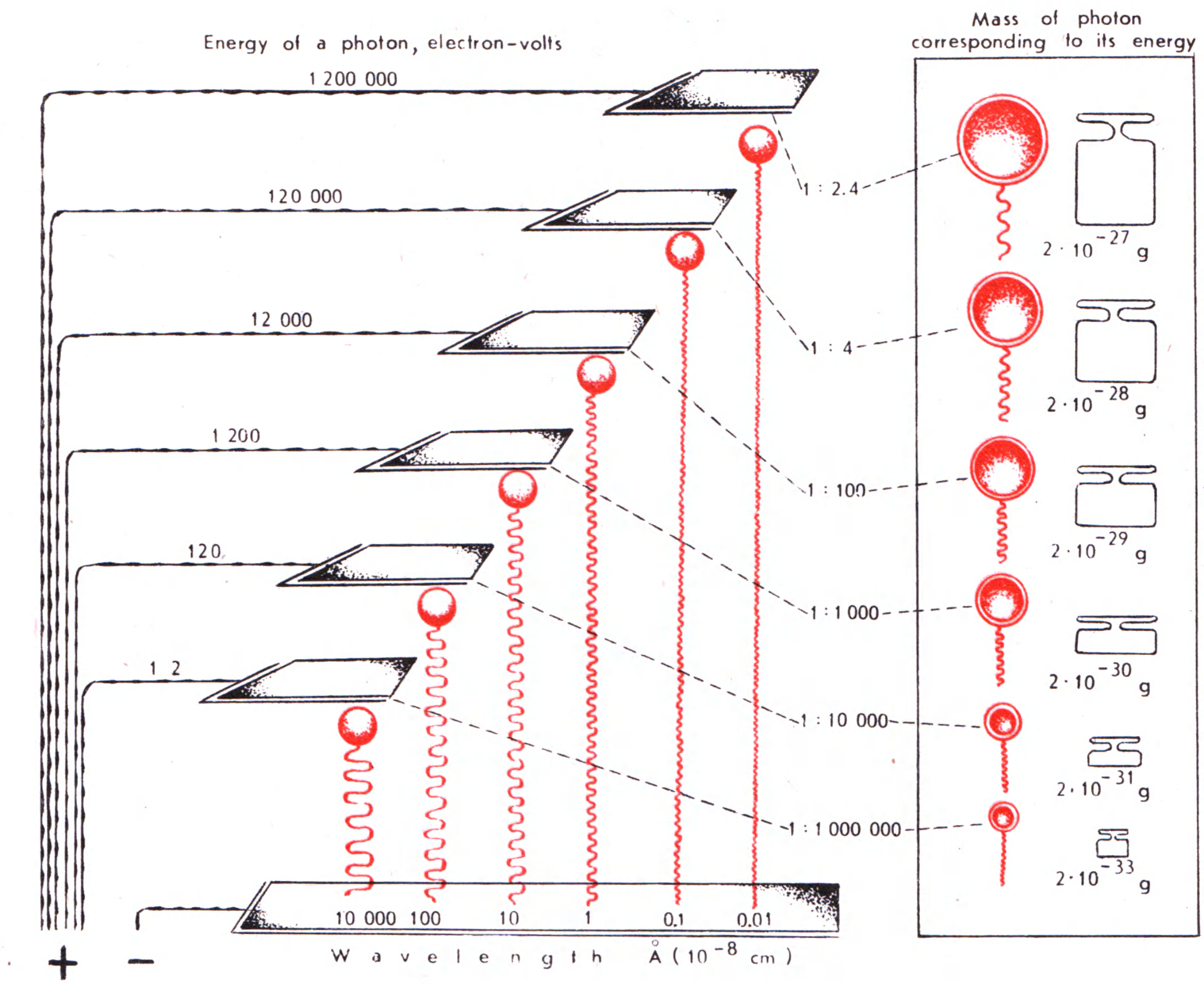
Compton's famous experiment. The wavelength of X-rays scattered by the atoms of a substance proves to vary according to their angle of reflection (increasing with increase of the angle)

magnetic radiation, i.e. the longer its wavelength, the greater is the energy carried by each quantum of the radiation.

Energy, however, can only be absorbed and emitted after it has acquired a strictly defined magnitude characteristic of the given physical process, and corresponding to a whole number of quanta. That, in turn, means that the energy of a quantum of ultraviolet light is considerably larger than that of a quantum of infra-red light, the energy of X-rays is higher than that of visible light rays, the energy of gamma-rays exceeds that of X-rays, etc.

The nuclear model of the atom, when proposed, enabled everything to be 'put in its place', and to explain and systematize the vast amount of confirmed experimental data accumulated and to give them a convincing theoretical interpretation. But physicists almost immediately stumbled across the first, and perhaps the most serious difficulty, which threatened to undermine the rising edifice of the new physics. The nuclear model unexpectedly proved to be in sharp contradiction with the fundamental laws and facts of mechanics and the theory of electricity.

The electron is a charged particle. As it rotates about the nucleus in a closed orbit, it continually changes its direction of motion, that is to say, it moves neither regularly nor uniformly. Then, again, any accelerated (or oscillating) electric charge should continuously emit electromagnetic (light) waves and so continuously lose energy. Its energy should finally be exhausted (and that rather quickly, in one thousand millionths of a second), and the electron fall into the nucleus. But an electron



The complicated dependence between the energy of a photon, the length of the electromagnetic wave corresponding to the photon, and the mass corresponding to its energy

does not lose its energy and does not collapse into the nucleus.

Later (in 1913), taking this into account, plus certain other contradictions encountered, Niels Bohr suggested that the electron was free to rotate around the nucleus only in strictly defined orbits, each corresponding to a quite definite level of atomic energy. The atom then does not emit light and, consequently, does not lose energy, and only emits light when one of its electrons jumps from one orbit to another closer to the nucleus. As a result, the energy of the atom falls immediately by a strictly defined amount, which is carried off by the quantum of light. On the contrary, when an atom acquires extra energy from outside (also not less than a strictly defined packet or quantum) then one of its electrons jumps from its orbit to another further away from the nucleus. This can happen when an atom collides with a fast electron from outside, or with another atom or particle; but the foreign particle must possess energy sufficient to knock the electron out of its normal orbit close to the nucleus to the next orbit or even

one more remote. It may even happen that the external energy will be sufficient for the electron to escape altogether from the atom. Then instead of a neutral atom two differently charged particles are formed, a free electron and a heavy, positively charged ion.

When an electric current flows through a gas, for example, its atoms absorb quanta of energy of a strictly definite amount, depending on the physical properties of the atoms, and pass into a higher energy (or excited) state, and one of the electrons of each atom jumps from an orbit close to the nucleus to one more remote. But atoms cannot remain in such an excited state for any lengthy period; the electron soon returns to its normal state (i.e. jumps back to the former orbit closer to the atomic nucleus), and as it changes orbit, the atom emits the excess energy released in the form of a quantum of light, or passes the energy onto another electron.

There can be successive emission of several quanta of energy of a definite size, or of a single quantum whose energy is two or three times that of several quanta.

This is the phenomenon that determines the distribution of the various lines in the spectrum of the light emitted by the gas.

When it is a matter of visible light, the emission is perceived by the eye as, for instance, quanta of red light (longer waves) or quanta of double energy or violet light (shorter waves). Naturally, our eyes do not perceive the quanta of other 'colours' with an energy less than that of red light (infra-red rays), or ultraviolet light, X-rays, and gamma-rays.

The nearer an electron is to the atomic nucleus, the greater the bond between them, and the greater the energy that must be expended to knock it out of the atom, or to transfer it to a remote orbit. And conversely, when returning to its former level close to the nucleus, the electron releases a quantum of light of larger energy than it would when it returns to an orbit less close.

Since light behaves both as a particle and a wave, the particle of light came to be called a photon. In principle there is no essential difference between it and other particles of matter. Particles merely have mass (and energy equivalent to it), but a photon has no mass. It is, nevertheless, quite material, being a certain packet of energy.

As a result of all the subsequent development of theoretical, mainly experimental, studies, the famous French physicist Louis de Broglie in 1925 formulated the hypothesis that was then literally in the air: that every particle with a certain velocity and, hence, a certain momentum (impulse), also has the guise of a wave. He furthermore derived a formula according to which the equivalent wavelength of a moving particle is

$$\lambda = \frac{h}{mv}$$

where h is Planck's constant, m the mass of the particle, and v its velocity.

This theoretical assumption was later substantiated by laboratory experiments. An electron beam directed onto the surface of a crystal or thin metal foil behaves exactly like X-rays or rays of light. Similar properties were observed in other particles, e.g. hydrogen atoms, the atoms of helium and neon, and later, neutrons. The higher the velocity of particles, or the greater their mass, the shorter was the wave corresponding to them, that is to say, the laws of the microworld are wave laws.

Another, very important fact, however, was also discovered, evidence of the infinite diversity of natural phenomena. The 'matter-waves' predicted by de Broglie, related to a moving particle,

were not electromagnetic waves, unlike X-rays or gamma-rays, although they might have similar properties (refraction, diffraction, interference, etc.).

The Great Law

But let us turn back again. In 1905, the same year as before, Einstein made a much greater discovery that radically altered notions about the nature of matter. It was not, strictly speaking, so much an isolated discovery, as a whole fundamental theory that has become known in science as the theory of relativity.

One of the most important conclusions of this theory was that no solid can move in air or vacuum with a velocity exceeding that of light.

The experiments already made in 1900 were the impetus to the development of this theory, for they had indisputably established that the mass of a moving electron differed from the mass of an electron at rest, and that it increased with an increase in its velocity.

That conflicted with Newton's hitherto predominant basic law of mechanics that the mass of a body is independent of its velocity and, hence, that any additional acceleration of the body should be proportional to the force applied to it. For instance, a projectile, leaving the barrel of a gun with a muzzle velocity of 1 000 m/sec, acquires a velocity of 1 300 m/sec if the gun is mounted on an aircraft flying at a speed of 300 m/sec and fired in the direction of flight; but if the gun is fired in the opposite direction, its muzzle velocity will be only 700 m/sec; in the first case the speed of the aircraft is added to the velocity of the projectile, and in the second case is subtracted from it.

Classical mechanics considered that a constant force acting upon a body would continuously increase its velocity until it finally reached or even surpassed the velocity of light.

But according to the theory of relativity that is impossible, since two quite different masses must be distinguished: (a) the mass of rest m_0 and (b) the mass m, corresponding to a body's velocity.

For low velocities v mass m is more or less equal to the mass of rest m_0; but as velocity approaches that of light, the mass m begins to increase rapidly. Thus, at a velocity of 282 100 kilometres per second the mass of an electron is almost tripled (2.957 times); at a velocity of 299 400 kilometres per second its mass is 20.58 times as heavy as that of an electron at rest.

Thus, the action of a force so increases the mass of a moving body that its velocity always remains less than the velocity of light.

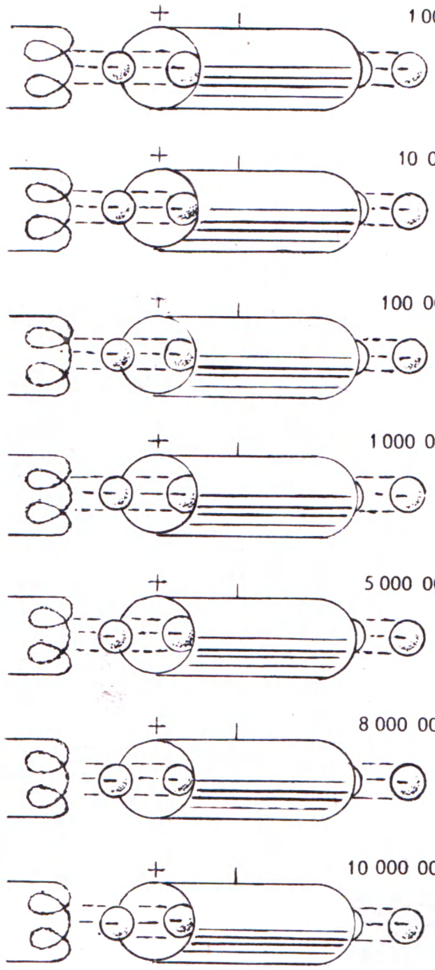
Mass and energy are interrelated. Any material body, be it matter or light, possesses mass and also has an energy proportional to its mass, and on the contrary, every material body that possesses energy also has a mass proportional to its energy.

Drawing on these conclusions and also on Lebedev's work on the pressure of light, Einstein derived a remarkable and outstanding equation linking mass and the physical measure of its movement, energy. (A similar expression for light had been derived by the Russian physicist S. Vavilov.) This relationship, which is still the most important fundamental law of modern physics, is expressed mathematically by the following formula:

$$E = m_0c_2,$$

where E is the energy of a body in ergs; m_0 is its mass at rest in grams; and c is the velocity of light in centimetres per second.

Thus, when the mass of rest is expressed in grams, the quantity of energy associated with it, expressed in ergs,



If an electron is accelerated to an energy of	Its velocity will be equal to	Its mass will increase by	Temperature of substance will be, °C
1 000 eV	18 720 km/sec	1.002	10^7
10 000 eV	58 470 km/sec	1.020	10^8
100 000 eV	168 200 km/sec	1.196	10^9
1 000 000 eV	282 100 km/sec	2.957	10^{10}
5 000 000 eV	298 500 km/sec	10.790	
8 000 000 eV	299 200 km/sec	16.600	
10 000 000 eV	299 400 km/sec	20.580	10^{11}

How the mass of an electron changes depending on its velocity

is the number of grams multiplied by the square of the velocity of light expressed in centimetres. Since light and, hence, a quantum of electromagnetic radiation, has mass, it also possesses an energy proportional to that mass.

When an excited atom emits a quantum of light (photon), it loses energy and together with it a definite mass, which is carried away by the photon. Before radiation this was the mass of a part of the electromagnetic field of the charges of the atom; after radiation

it became the mass of a photon, which can only travel at the velocity of light.

It is necessary, however, to distinguish between the energy related to mass and the energy of moving atomic particles. The energy related to mass can be represented as intrinsic energy, the energy of 'existence' of matter. Matter has a store of energy due to its very existence. In that respect a material particle is nothing but a concentrated packet of energy localized in space and proportional to the mass of the particle at rest. But when a particle is not at rest but moving, it acquires additional energy, kinetic energy due not to inner sources but to the energy of the external agent that put the particle into motion. A particle deprived of mass, like the photon, for instance, only possesses kinetic energy, but has no intrinsic energy, related to mass.

And here we must emphasize especially that matter is never transformed into energy, nor energy into matter, as some physicists have tried to argue, drawing erroneous conclusions from Einstein's work, for such transformations never have and never will occur.

Energy is inconceivable, isolated from matter, and it can only exist where there is matter; consequently, motion and energy exist only as the motion and energy of matter.

A little later Einstein suggested that the phenomenon of radioactivity, because it was accompanied by the release of large quantities of energy, made it practically possible, in properly mounted experiments, to verify the relationship between mass and energy that he had derived. In particular, he wrote: "The mass of a body is the measure of energy content in this body; if the energy varies by a factor of 4, the mass varies in the same direction by a magnitude $\frac{4}{9\times10^{-20}}$ with the energy being measured in ergs and mass in grams. It is possible that a checking of the theory may prove to be successful, operating with bodies whose energy content is extremely variable (radium salts, for instance)."

What is 'Mass Defect'?

Application of Einstein's equation to the problems we are considering throws light upon all the earlier guesses made by scientists about the tremendous stores of energy within the atom and connected with the motion of its constituent elementary particles.

When a certain reduction of the mass of a substance takes place during a nuclear reaction, it is inevitably accompanied with the release (emission) of a large quantity of energy.

Why, then, do we usually never observe any increase or decrease in the mass of a body whose energy increases or diminishes noticeably, for instance, when it is strongly heated or cooled? The secret involved is simple.

Let us assume that we have heated a ton of water to 100°C. The velocity of the water molecules will be much increased owing to the increase in temperature. The energy acquired during heating will have made the water about 5 millionth of a gram heavier (to be precise, 4.65×10^{-6} g). But it is practically impossible to detect such a small gain in mass.

In the world of atomic particles we deal with velocities of motion thousands of times greater than the velocities of the molecules in a heated substance. For instance, a beta-particle (electron) may escape from the nucleus of a disintegrating atom with a velocity bordering on 248 000 kilometres per second. At that velocity its energy increases to such an extent that the gain is accompanied with an increase in its mass by a factor of about 1.78, a fact that was

brilliantly confirmed when powerful modern particle accelerators began to be used.

If all the power generated in a year by one of the hydroelectric stations on the Volga were used to charge a fantastically big accumulator, it would gain no more weight than 400 grams.

If we take a certain amount of matter, say one gram, its energy and related mass should be equal, according to Einstein's equation, to its mass multiplied by the square of velocity of light, i.e.

$$E = m_0c^2 = 1(3 \times 10^{10})\ (3 \times 10^{10}) = \\ = 9 \times 10^{20} \text{ ergs}$$

Let us recall that an erg is an exceptionally small quantity and serves as the measure of the work done when a body acted upon by a force of one dyne is displaced through one centimetre. It is so small that the ordinary unit of electric energy, the kilowatt-hour, is equal to about 3.6×10^{13} ergs. Nevertheless, the quantity of energy, calculated by the above formula, that would be released by one gram of matter if its whole mass were transformed into photons of radiation, would be so large as to equal, no more and no less, 25 million kilowatt-hours, an amount of energy as great as that generated in a year by a large power station.

One kilogram of matter, be it coal, stone or eider-down, could theoretically release energy equal to 25 000 million kilowatt-hours, while burning one kilogram of coal liberates only 8.5 kilowatt-hours. The difference is appreciable, a factor of about 3 000 million.

It does not follow, however, from these calculations that men will ever succeed in liberating all the energy in matter. Indeed, to overcome the forces binding the particles of the atomic nucleus together, it is first necessary to expend a certain amount of energy coming from an external source. Only then does the disintegrating or de-arranging nucleus, having lost some of its particles, release the energy associated with these particles. After the energy is released, the mass of the nucleus proves to be smaller than the combined mass of the original (unexcited) nucleus and the lost particle. This difference, naturally, is the larger, the greater was the energy released in the formation of the new nucleus (or rather, the closer the remaining nucleons of the nucleus are to each other, or in other words, the more closely they are packed).

The most 'closely packed' nuclei are those of the elements located in the middle of the Periodic Table, between silicon-14 and tin-50. So, it comes about that the elementary particles are not always bound in an atom in such a way that the energy liberated by the disintegration of an atomic nucleus, or during its rearrangement, is larger than that expended on splitting it. Consequently, in order to obtain energy, it is more advantageous to smash or rearrange only the atoms of those elements for which the expenditure of energy on splitting is smaller than the energy liberated.

From the point of view of nuclear physics we live in a world of an infinitely large number of the most diverse kinds of spring, all tightly wound up in the process of formation, and each of which can be released and perform work, as it unwinds, liberating the energy hidden in it. And clearly, since the springs can be unwound, it is also possible to try and wind them up artificially. At present man is interested in unwinding the springs by releasing the catches, and finding out beforehand which of them can be released with the least possible expenditure of energy. But it would be better still, if we were

able, by releasing a small spring to remove the catches on some very large springs.

Let us begin with the largest 'springs' yet known, although (as we already know) men first succeeded in releasing a small 'spring'. We already touched on its origin, when we spoke about the experiments of Cockroft and Walton.

The atomic nucleus of helium consists of two protons and two neutrons. To split it into its elementary particles, it is necessary to overcome the tremendous forces of attraction that retain the nuclear particles and that act within a distance of about two nuclear diameters. To do so, of course, a quite large amount of energy must be expended, by hitting the helium nucleus with, for example, some heavy particle accelerated to enormous velocity. As soon as the particles of the smashed nucleus fly further than two nuclear diameters, the intranuclear forces cease to act, and are replaced by the repulsive force acting between the two positively charged protons, which will then fly off in different directions with no less immense energy. From that moment the splitting of the nucleus will no longer absorb energy, but will release it.

It would be logical to assume that when the particles combine to form the nucleus of a helium atom, it will first be necessary to overcome the very strong repulsive force, exerted by the two positively charged protons, and that only after they have been brought into the sphere of action of the forces of intranuclear attraction will they be compressed still more, and their mass decrease; and this decrease in mass will be accompanied with a release of energy. This energy will not, of course, be liberated as a weightless, non-material substance. It will be carried by real quanta of high-energy radiation, by the excess electrons and positrons of the helium atom, and by other particles and emissions.

Such a decrease in the mass of a substance after the release of energy is known as mass defect.

Let us check this not altogether exact, but more or less illustrative, picture of the change in the mass and energy of matter associated with the rearrangement of nuclear particles, by considering the formation of a nucleus of helium ($_2He^4$) from two protons and two neutrons.

The total mass of the protons and neutrons from which the helium nucleus is formed is:

$$2 \text{ protons} \times 1.0076 + 2 \text{ neutrons} \times \times 1.0089 = 4.033 \text{ atomic mass units(amu)}$$

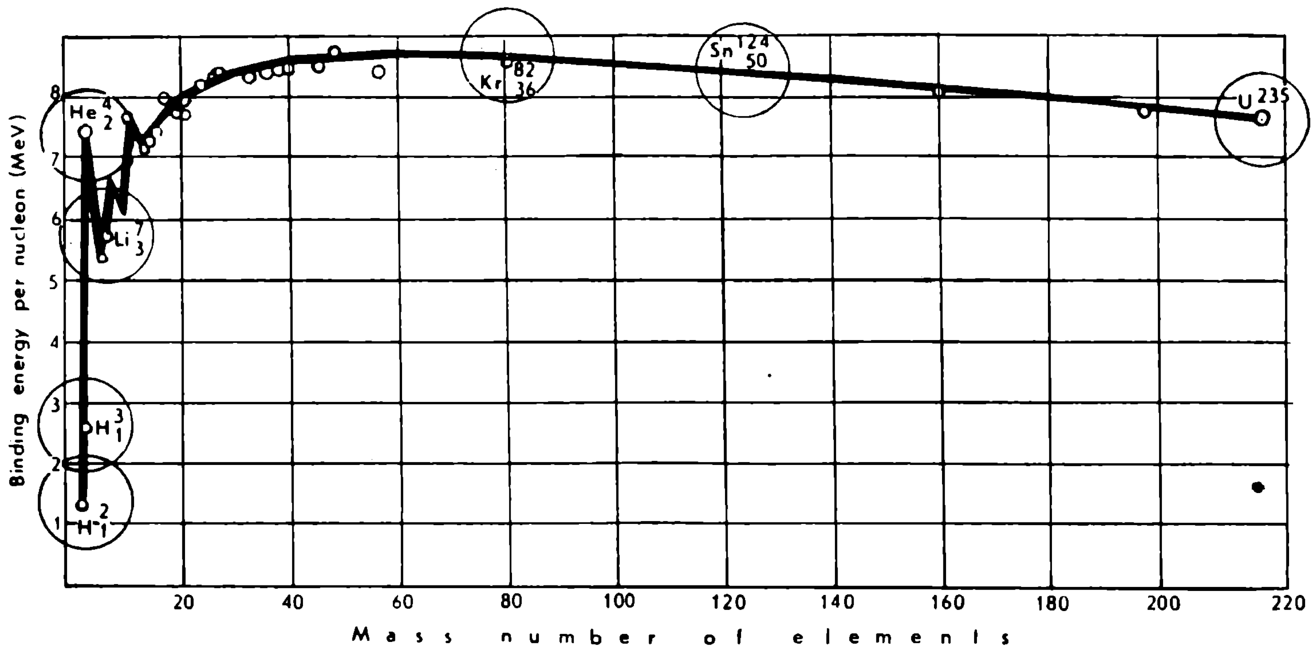
But the mass of the nucleus of helium formed from these particles, and measured by modern methods is exactly (less the mass of two electrons) 4.003 atomic mass units; the difference is 0.03 amu. Expressing this quantity in units of weight, the mass defect observed in the formation of one gram-atom of helium (a quantity whose weight in grams is numerically equal to the atomic weight of the chemical element, i.e. four grams) is 0.03 gram. From the mass-energy equation it follows that this reduction in mass is accompanied with the release of energy to the amount of

$$E = mc^2 = 0.03(3 \times 10^{10})^2 = = 2.7 \times 10^{19} \text{ergs}$$

or more than 750 000 kilowatt-hours!

If a power station with a capacity of 100 000 kilowatts used protons and neutrons as fuel, as they formed the helium nuclei, instead of burning coal, it would consume a mere 12.8 grams a day, and only 4.5 kilograms a year, compared with 500 000 tons of coal!

Thus, the uniting of several indivi-



Graph showing binding energy per nucleon for various elements of Mendeleev's Periodic Table

dual particles into an atomic nucleus, with the release of so much energy, is a very complex process differing essentially from the simple addition of protons and neutrons. A profound, qualitative rearrangement or reconstruction of matter takes place.

By calculating the nuclear mass of other elements in the same manner, it can be seen that it is always smaller than the sum of the masses of the separate protons and neutrons from which the nucleus concerned is composed.

Mass defect is observed, and plays a major role, not only when protons and neutrons combine to form an atomic nucleus, but also when the nucleus of a heavy element splits into two lighter elements.

The energy required to form the nucleus of any chemical element from protons and neutrons is known as the nuclear binding energy.

Nuclear Binding Energy

In the abstract case of the formation of the nucleus of helium from two protons and two neutrons, that we have been considering, the energy liberated, i.e. the nuclear binding energy, was 28 MeV.

Now, since the nucleus consists of several particles (called nucleons) each nucleon is responsible only for a fraction of the total energy, a fraction which is known as the average nuclear binding energy. For a helium nucleus, consisting of four nucleons, the average binding energy is 28 : 4=7.0 MeV per nucleon.

In the Cockroft-Walton experiment mentioned above the union of a proton with an atom of lithium and the formation of two alpha-particles released 17.2 MeV (about 8.5 MeV for each nucleon, plus 0.125 MeV, the energy of the bombarding proton).

One can thus calculate both the total and the average binding energy of the nucleus of any chemical element in

the Periodic Table. Data on average binding energies are given in the graph shown on p. 94.

The atomic weight of the elements (their mass numbers) is plotted on the horizontal axis, and the average binding energy per nucleon expressed in millions of electron-volts on the vertical axis. This little graph explains a lot about what had not been understood in nuclear physics.

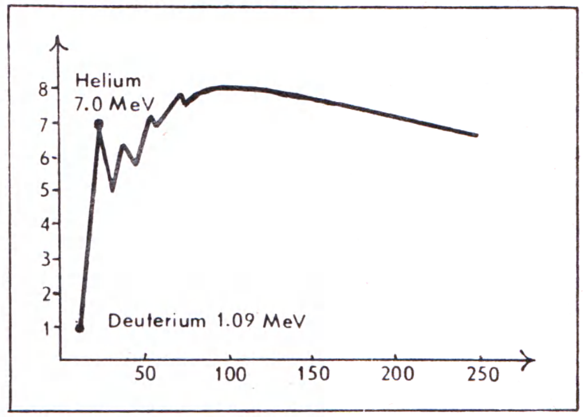
For one thing, it makes it possible to determine exactly when this binding energy can be liberated and when it cannot.

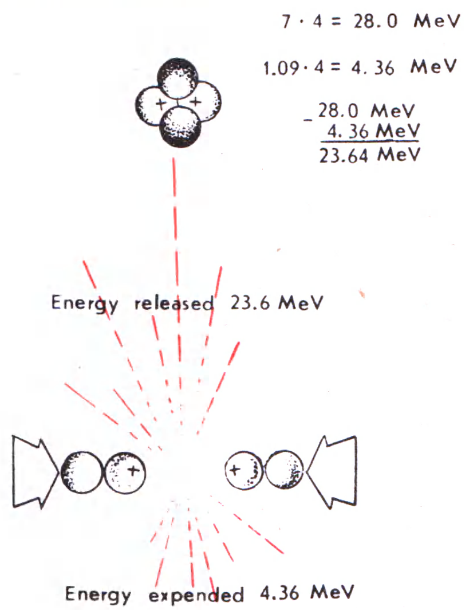
And for another thing, it can be established from the graph how much energy can be released through nuclear fission and how much through fusion (synthesis), i.e. which nuclei should be combined and which split in order to obtain energy.

For some time after means of releasing nuclear power had been discovered, and even occasionally now opinions are expressed that in time people will learn how to release and utilize the enormous energy locked up in any stone lying on the road or in a handful of sand. These more than optimistic beliefs have arisen from a misunderstanding of the Einstein's famous equation of the interrelation of mass and energy, $E=mc^2$, according to which, as energy is released during nuclear fission or synthesis, the mass of the original nuclei involved diminishes.

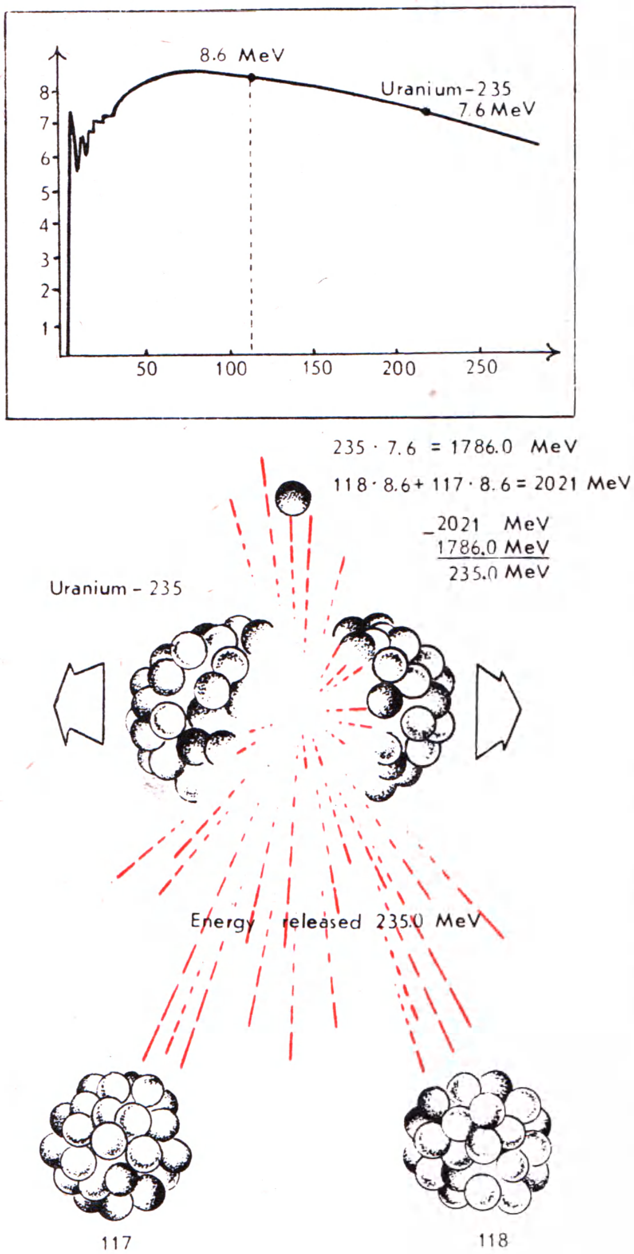
Hence two conclusions were drawn. First: if the whole mass of the material involved turned into energy, each gram of the substance would yield 25 million kilowatt-hours of energy; and second, since all substances possess mass, any substance, including a roadside stone, could be converted into energy.

The error of these assertions is that energy can vanish or be carried away only by an elementary particle or quantum of radiation, and in order to fly





Energy is first absorbed, then released, provided that a helium nucleus is built up from two nuclei of deuterium



This is how much energy is released by the nuclear fission of a heavy element, say uranium-235, into two fragments, each with an atomic weight of 117 or 118

off these particles must have a certain energy.

From the graph it can be seen that the highest average binding energy, equal to about 8.6 MeV per nucleon, is found in the nuclei of chemical elements in the very middle of the Mendeleev Table. No matter in what combination the nuclei are rearranged, the amount of energy expended on the operations will be equal to the energy released. Consequently, nothing practical can be gained by it.

But elements at the very beginning and the very end of the curve have a considerable variation of average binding energy per nucleon, and there one can select combinations of nuclear reaction that will yield a considerable gain in energy.

Let us consider three examples.

1. What will happen when a nucleus of helium is formed from two nuclei of heavy hydrogen (or deuterium) $_1H^2$?

The total binding energy of a helium nucleus, consisting of four nucleons, is 28 MeV.

The total binding energy of a deuterium nucleus, consisting of two nucleons, is $2\times1.09=2.18$ MeV.

Thus, when a helium nucleus is formed from two nuclei of deuterium energy will be released, equal to the difference between the binding energy of helium and that of two nuclei of deuterium:

$$28-(2\times2.18)=23.64 \text{ MeV}$$

This is the highest energy that it is possible to obtain from the fusion of light nuclei into a heavier one.

That is quite understandable. When there are few nucleons, it is difficult to arrange them so that they will occupy the most advantageous, i.e. the most compact, volume, which is a sphere. No matter how the nucleons are arranged or packed, the figure formed by them will be either prolate (for instan-

ce, a deuteron, consisting only of two nucleons) or angular (a triton). To form a figure as close to a sphere as possible, a comparatively large number of nucleons must be present. Consequently, it is possible to obtain a more compact nucleus when four nucleons are combined..The average distance between them will be reduced, owing to which a corresponding amount of energy will be released.

Let us see how much energy would be released by the formation of one kilogram of helium.

One gram-atom of helium ($_2He^4$) contains 6.02×10^{23} atoms (the Avogadro number), so that one kilogram contains a total of $\frac{6.02\times10^{23}}{4}\cdot 1\,000=1.505\times10^{26}$ atoms.

When one kilogram of helium is produced from deuterium nuclei, the energy released will be

$$1.505\times10^{26}\times23.64=35.6\times10^{26}\ \text{MeV}$$
$$\text{or } 1.36\times10^{14}\ \text{calories}$$

To obtain that amount of energy in another way, it would be necessary, for instance, to burn 13 600 tons of petrol.

2. What happens when the nucleus of a heavy element like uranium-235 splits into two fragments?

Like the lightest nuclei, heavy nuclei are not packed as tightly as nuclei of medium mass. This is because of the effect of the large number of protons, which, owing to their identical electric charges, tend to repulse one another. Heavy nuclei are not only packed less densely, but contain a greater number of neutrons than protons, compared with nuclei of medium mass. When a heavy nucleus splits, its nucleons become distributed into two nuclei of medium mass, packed more densely than before.

The atomic weight of uranium-235 is 235.118, and the mass of a neutron is equal to 1.009. Thus, the mass of the particles taking part in the fission reaction is 236.127 atomic mass units.

During fission the nuclei of uranium-235 split in various ways, but the fission products usually have mass numbers of 95 and 139. Their sum is but 234 instead of 236.127 amu, since several neutrons are always released in the process. The atomic weights of the stable isotopes molybdenum-95 and lanthanum-139 are respectively 94.936 and 138.960. If we add to them 2.018, the mass of two free neutrons, we then have a total of 235.904. The mass vanishing in the course of fission is $236.127-235.904=0.223$ amu. If this figure is multiplied by 931 million electron-volts (the energy corresponding to one atomic mass unit), the energy released by fission can be expressed as $0.223\times931=208$ million electron-volts.

A roughly similar result would be obtained, if we began with the average binding energy of atomic nuclei.

Let us take the atomic weight of each fragment as approximately $235:2=118$ atomic mass units, a weight characteristic of elements occupying the middle of the Periodic Table, and possessing the highest binding energy per nucleon, 8.6 MeV.

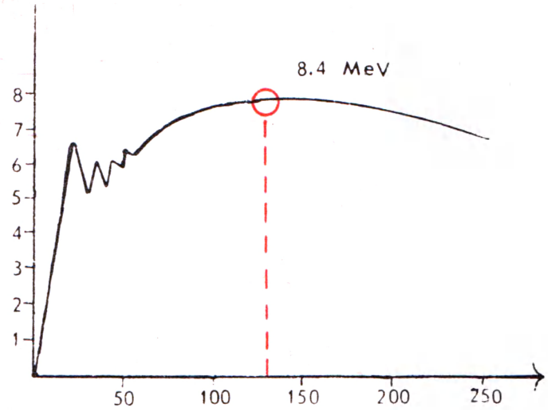
The total binding energy of a uranium-235 nucleus, containing 235 nucleons, is $235\times7.6=1\,786.0$ MeV. The binding energy of the two equal fragments that are the nuclei of lighter elements is

$$118\times8.6+117\times8.6=2\,021.0\ \text{MeV}$$

Consequently, the difference between the energy of the atomic nucleus of uranium-235 and the energy of its two fragments is

$$2\,021.0-1\,786.0=235.0\ \text{MeV}$$

Nuclear fission of all the atoms of one kilogram of uranium-235 yields an energy equivalent to about 1.96×10^{13} calories, which is the same as can be



Will energy be released by the nuclear fission of elements in the middle of Periodic Table?

obtained by burning 1 800 tons of petrol.

Thus the fusion or uniting of the nuclei of light elements yields eight to ten times as much energy as the fission of heavy elements.

3. What would happen if we produced fission of the nuclei of elements from the middle of the Periodic Table?

As an example, let us take a nucleus with a mass number of 118 (tin) and assume that it splits into two halves, forming two nuclei of an element with a mass number of 59 (cobalt or nickel).

From the graph on page 94 we find that the binding energy per nucleon for a substance with an atomic number of 118 is 8.4 MeV, and for a substance with a mass number of 59 is 7.5 MeV. The total binding energy of the nucleons of tin is

$$118 \times 8.4 = 991.2 \text{ MeV}$$

The binding energy of the nucleons of the fragments is

$$(59 + 59) \times 7.5 = 885.0 \text{ MeV};$$

$$885.0 - 991.2 = -106.2 \text{ MeV}$$

It would appear that to split the nucleus of tin into two halves it is necessary to expend an additional amount of energy, equal to 106.2 MeV, gaining nothing in return. Thus, a cobblestone will remain a cobblestone for a very long time, perhaps forever if no new discoveries are made, unless by chance it happens to be a piece of uranium ... or of granite.

You may well ask: why granite?

Because ordinary granite proves to contain quite a real source of nuclear power, though of another nature. One hundred tons of granite may contain around 400 grams of uranium and one kilogram of thorium. In that case, the energy hidden in it is equivalent to the chemical energy contained in about 5 000 tons of coal. It is only in this sense can a cobblestone in fact prove to be a source of energy.

In addition to uranium and thorium, 100 tons of granite contain eight tons of aluminium, five tons of iron, two tons of magnesium, 90 kilograms of manganese, 35 kilograms of chromium, 20 kilograms of nickel, 15 kilograms of vanadium, ten kilograms of copper, five kilograms of tungsten, and even two kilograms of lead.

Fortunately, both the uranium and the thorium in natural granite are bound with substances constituting less than one per cent of its whole mass. In due course, it may prove profitable both economically and technologically to extract fissile materials from granite, and as by-products scarce materials much needed in modern metal industries.

But for that purpose it would be necessary to crush and grind the granite, subject it to concentration, and separate the useful minerals from it, operations that are all well known in mining.

And if, to begin with, we only succeeded in extracting 20 per cent of the uranium and thorium in the granite, 100 tons would still be equivalent to 1 000 tons of coal, as regards energy.

The energy or power expended on the work of extracting, cutting, crushing, grinding, concentrating, and transporting the granite will be covered by the burning of about three tons of coal, so that the net gain would be equal to the energy contained in 997 tons of coal.

In terms of money the ratio between the cost of the nuclear fuel, extracted from so unusual a source, and the energy released from it, does not happen to be as favourable as that for extracting uranium and thorium from the ores normally used. But man, who is primarily interested in extracting nuclear fuel, will obtain a new, and almost inexhaustible source of fissile material, since granite is one of the commonest minerals on Earth.

But What is Radioactivity?

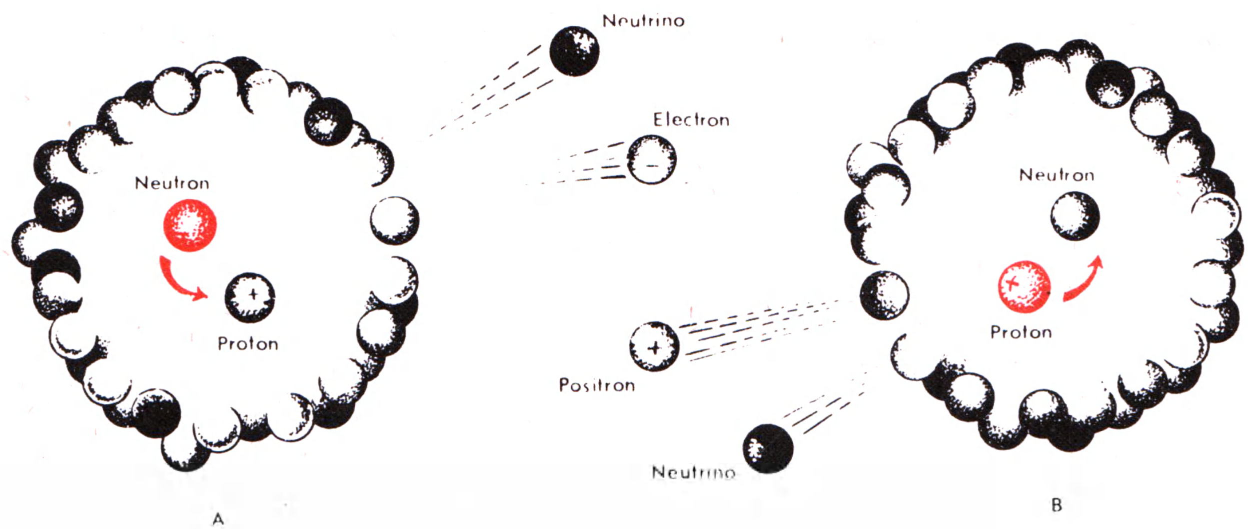
As was to be expected, scientists spent much time and effort on studying mainly the external properties of radioactive substances, the more so since these properties were so astounding and unusual. But it soon became necessary to gain an understanding, even if only of the general feature, of the mysterious mechanism governing the spontaneous decay of radioactive elements, with its accompanying emission of alpha-particles, beta-particles, and gamma-rays, and in the case of artificial radioactivity of positrons, too. The emission of alpha-particles was more or less understandable; they were particles that broke off from the atomic nucleus and were thrown out of it as the result of some internal instability, or were knocked out of it after it had been hit by some high-energy particle. But where did beta-particles, that is to say electrons, come from? For, as had been established, the nucleus consisted only of protons and neutrons.

The only thing that could be assumed was that electrons suddenly appeared in the nucleus as the result of some intranuclear transformation, and only at the moment of radioactive transmutation. Later scientists succeeded in observing these events, in studying the spontaneous radioactive decay of the atom of tritium, the nucleus of which contains one proton and two neutrons. Its spontaneous radioactive decay results in the formation of a nucleus of the isotope helium-3, which consists of two protons and one neutron, with the emission of one free electron. A neutron disappears somewhere, but is replaced by a proton and an electron. It turned out that the appearance and emission of the electron were due to the transformation of a neutron into a proton.

We have already described a nuclear reaction in which the nucleus of the decaying atom emits a positron instead of the electron, that is, a particle exactly similar to an electron, but carrying a positive electric charge, rather than a negative one. The radioactive isotope nitrogen-13, consisting of seven protons and six neutrons, decays into an atomic nucleus of carbon-13, containing six protons and seven neutrons, emitting a positron in the process.

It was guessed that protons and neutrons could be transformed into one another during the radioactive disintegration of unstable or excited nuclei, and the excess positive or negative charge carried away by an electron or a positron. This disintegration was continuously accompanied by the decay of countless radioactive daughter elements, many of which, like radium, decayed over the course of millenia, and others in the course of a thousandth or a millionth of a second!

Taken together, all these facts allowed the proton and neutron to be considered one particle, which is why they



In radioactive disintegration of an atomic nucleus, a beta-particle (electron) will only be ejected if one of the neutrons of the unstable (excited) nucleus turns into a proton (*A*). The resulting atom preserves its mass, but owing to the unit increase in its nuclear charge, it becomes a light isotope of the element lying one place to the right in Mendeleev's Table. When radioactive disintegration is accompanied by the ejection of a positron (as happens during the disintegration of artificial radioactive elements), one of the nuclear protons turns into a neutron. The resulting atom also preserves its mass, but because its nuclear charge has become one unit less, it is transformed into a heavy isotope of the element lying to its left in the Periodic Table (*B*)

were termed nucleons, which could, however, exist in two states, as a *proton* or as a *neutron*. Now let us try to look into other peculiarities of the radioactive transmutations of atomic nuclei. It is already clear to us that with beta-decay one of the neutrons of the nucleus turns into a proton. And then, and then only, one electron appears, the charge of which should compensate for the positive charge of the newly formed proton; but this electron happens to be in surplus to the 'housekeeping' of the nucleus, and, by force of the laws of the nuclear reactions of beta-decay, must immediately get out.

This beta-particle cannot even remain within the atom (in one of its electron shells), since its energy is tens and hundreds of thousands of times greater than that of the orbital electrons. The positive charge of the atom is now one unit larger. As a result the nucleus of a new atom is formed, of a heavier element, it is no longer tritium but helium, for instance.

The proton in turn may also be transformed into a neutron. But, then, its positive charge must vanish somewhere. It is carried off by a positron and, as a result, a new element of the Periodic Table appears, whose atomic weight is one unit smaller, and we have, for instance, carbon-13 instead of nitrogen-13.

After everything had been neatly pigeon-holed, another, new discrepancy arose. The mass equivalence of the energy of a proton and a positron is not quite equal to that of a neutron, and the energy equivalence of the mass of a neutron and electron is even less than that of a proton, i.e. the energies do not balance. With each transformation the nucleus actually loses a definite amount of energy, carried away by an electron or positron, but some energy still disappears somewhere. Certain scientists, arguing

from the standpoint of idealist philosophy, proclaimed with joy the downfall of the law of conservation of energy.

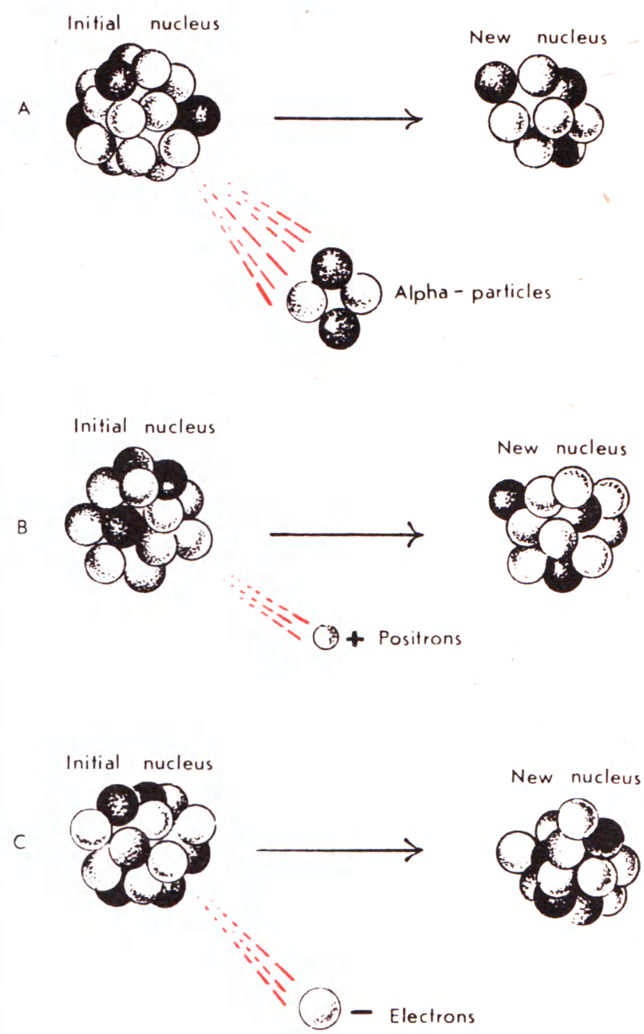
Their joy, however, did not last long. It was soon shown that, in addition to the electron or positron, and simultaneously with it, the nucleus emitted another particle, without an electric charge and possessing insignificant mass, but moving at a velocity close to that of light. The new particle was given the name of *neutrino*, or small neutron, and it is the neutrino that accounts for the missing energy that prevented an exact energy balance from being struck.

Thus, the transformation of a neutron into a proton involves the emission of an electron and a neutrino, and the transformation of a proton into a neutron, the emission of a positron and a neutrino. The inverse reactions are also possible.

But what is it that gives rise to electron or positron decay of the nuclei of radioactive elements? And why do they emit electrons in some cases, and positrons in others?

Certain laws that apply only to the microworld helped to solve this puzzle.

We already know that the electrons rotating round an atomic nucleus are not arranged in any odd manner, but are strictly organized in orbits, corresponding to their energy levels, and obeying strictly defined *quantum laws*. Since all atomic particles and not only electrons obey quantum laws, there were reasons for supposing that the energy levels of particles (nucleons) also caused them to be arranged in a certain order in the nucleus, and that nucleus, just like the electron shell of the atom, had a laminar structure, although it had no fixed centre, as the atom did. Each energy level could accommodate a certain number of nucleons. It was calculated that the lowest level would contain only four particles, two protons



The three most important models of radioactive decay of atoms: *A*, decay with the ejection of alpha-particles; *B*, with artificial radioactivity, the atomic nuclei eject positrons; *C*, decay with ejection of electrons

and two neutrons. And the nucleus of helium has just such a first shell, which explains why it is one of the strongest formations among all the nuclei of the light chemical elements.

Other laws also were discovered. For instance, nuclei with 2, 8, 20, 50, 82, and 126 nucleons were especially stable as regards radioactive disintegration. Physicists have called these the 'magic' numbers, for it is atoms with such numbers of nuclei that are most common in the universe. But some are stronger than the others, especially those in which the number of either the protons or the neutrons, or better still of both, corresponds to a 'magic number'. Again helium can be cited as an example.

But what holds good for nuclei of light or medium mass begins to misfire nearer the end of the Periodic Table.

According to the shell model of nuclear structure the nucleus, it seemed, should contain equal numbers of protons and neutrons. But the difficulty in keeping to this order was that all nucleons of a nucleus must occupy the lowest energy level when it was in its normal, unexcited state. But, by analogy with the electron shells, any level could only accommodate two like particles, either two protons or two neutrons. Therefore, there was simply no place at the prescribed energy level for many of them, and the nucleons would have to occupy an unpermitted level, thereby disturbing the stability of the nucleus as a whole to some extent.

Another complication is that two kinds of force are in constant action in the nucleus, namely, the electrostatic repulsive (Coulomb's) force acting between the positively charged protons, and the attractive force acting between all nucleons, protons and neutrons. Therefore, to produce the nuclei of the more complicated and heavy elements, nature had to solve a complex energy equation with many unknowns, and above all, to create them in such a way that they would not break up when subjected to all these opposing factors.

A large nucleus contains many protons. The electrical forces of repulsion 'loosen' it to some extent, and it is impossible naturally to add more protons to a large nucleus, since that would reduce the binding force of the whole nucleus. So, the neutral neutron is forced to move to a higher energy level, for there is no more place for it at the lower level, all the places being occupied by other nucleons. The addition of a neutron, which is unaffected by electrical forces, strengthens a nucleus and makes it more stable, although the presence of neutrons at higher-energy levels makes the whole nucleus more excited. Equal numbers of protons and neutrons are therefore characteristic only of the lightest nuclei. But this convenient symmetry becomes disturbed later in the Periodic Table, and the medium and heavy nuclei are strengthened through an increase in the number of neutrons in them.

But everything comes to an end. The repulsive electrical forces become so great in heavy nuclei with their large number of protons that even with a large excess of neutrons the nuclei gradually lose their stability and begin to disintegrate, emitting alpha-particles, electrons, and gamma-rays, and tend to decay until they reach a stronger combination at which radioactive disintegration ceases.

When a nucleus happens to contain too many neutrons, it acquires stability and strength by ejecting an electron (and neutrino) in the course of radioactive disintegration and converting one of its neutrons into a proton. But if it has an excess of protons the opposite happens, a positron (and a neutrino) is

ejected, and one of the protons is transformed into a neutron.

It happens often that, in ejecting an electron or positron (with a neutrino), and replacing a proton by a neutron, or vice versa, a nucleus does not acquire proper stability, and the desired internal rearrangement does not occur. The nucleus is then forced at once to eject an alpha-particle, i.e. two protons and two neutrons, so at last, after a certain number of beta-disintegrations, to find peace and quiet in the stable isotopes of lead. As we already know, there are three natural radioactive disintegration series: the uranium, the thorium and the actinium. Let us consider one of them. The nucleus of uranium-238 in disintegrating ejects an alpha-particle, and turns into a nucleus of thorium-234.

But the latter also happens to be unstable, and besides is overloaded with neutrons. One of them, therefore, becomes a proton, and an electron and a neutrino are ejected from the nucleus. The result is a nucleus of protactinium-234, which, on losing a positron and neutrino turns into a nucleus of uranium-234 in an exactly similar way. But the play of forces within the nucleus continues, and it still remains excited. Therefore, a long series of transformations occur with the emission of alpha-particles, and occasionally of gamma-rays. Finally it becomes the turn of lead-214. But it too proves to be unstable, and on emitting an electron, this isotope of lead turns into bismuth-214, which, after losing an alpha-particle, is transformed into thallium-210. But it still proves impossible to retain the excess neutrons in the nucleus; three times more neutrons turn into protons, emitting positrons, until the ill-fated nucleus becomes polonium-210. From it finally the saving alpha-particle escapes, and the nucleus, after having suffered so many transmutations, comes to rest in the stable isotope lead-206.

Of course, if the nucleus of uranium-238 had originally a different composition, such a long series of transformations would not be required. In fact there are quite stable nuclei of more lucky elements that are heavier than lead. But, because they were not composed in a proper way from the outset, the nuclei of uranium-238, and of the progenitors of the other three radioactive series, have to drain the cup of disintegration to the dregs, and in the search for stability to become lead, with no chance of stopping somewhere half-way. The process takes a rather long time, naturally. Several thousand million years must pass for all the nuclei of natural atoms of uranium-238 to disintegrate and turn into lead.

In the nuclei of artificial radioactive isotopes the ratio of neutrons to protons happens to be small, which is the cause of the development of positron activity.

In a number of cases an entirely different kind of disintegration takes place. Instead of the transformation of a proton into a neutron, with the emission of a positron (and a neutrino), the nucleus of the atom captures one of its electrons, usually from one of the inner orbits (nearest to the nucleus), which immediately combines with a proton to form a neutron. In consequence, the nucleus becomes that of the element whose atomic number is smaller by one, but which has the former mass number, in other words, it turns into an isomer of the atom of the new element. To illustrate, the nucleus of beryllium-7 can thus turn into the nucleus of lithium-7. This mode of beta-decay is referred to as K-capture.

K-capture is usually observed with the nuclei of heavy elements, since nuclear radius increases with increase in positive charge, while, on the contrary,

the radii of the inner electron orbits become smaller so moving closer to the nucleus.

Since K-capture removes an electron from the electron shell of the nucleus, this transformation of the nucleus of an element into that of another is accompanied with the emission of a neutrino and of an X-ray quantum.

Thus, the general term beta-decay covers three independent forms of radioactive transformation: negative-beta decay proper (emission of an electron); positive beta-decay (emission of a positron); and electron-capture or K-capture (capture of an orbital electron by the nucleus, mainly from the shell nearest to it).

Other forms of radioactive transformation are known. Some of them we shall not touch on because of the complexity or obscurity of the phenomenon itself, but one or two we shall discuss elsewhere in our book.

Scientists have accumulated an immense store of facts and laws that enable us to estimate the instability or stability of various nuclei, to predict how a radioactive nucleus will be transformed, and to forecast whether the isotope formed will be short-lived or long. But science still cannot answer the basic question of which atoms will decay first and which later, and what it is that causes the disintegration. The only thing known in this connection is that radioactive decay is preceded by the accumulation of very important internal contradictions of some sort within the nucleus.

There are grounds for believing that the riddle of radioactivity will be answered when we can solve another puzzle, the even more complicated problem of the nature and mode of action of intranuclear forces.

Briefly About Heat

The most remarkable property of energy is its capacity for transformation. One of the commonest forms of energy in nature is kinetic energy or the energy of movement. Heat, or thermal energy, is a reserve of kinetic energy in the form of incessant and chaotic movement of molecules or atoms. The amount of heat in any body is measured by a special conventional quantity, *temperature*. With a high level of energy the particles of a substance move faster and collide more frequently and more forcefully with other particles. Consequently, a high temperature corresponds to a high level of thermal energy. At a low level of energy the velocity of the particles is lower and the number of collisions is less; and consequently, a low temperature corresponds to a low level of energy.

The temperature of a body or substance is determined by the *average energy* of all its moving particles. In fact, whenever chaotic, random movement of particles predominates, particles of various energy can be found, i.e. particles moving at very different velocities. If it were somehow possible to sort the particles of a substance, according to their energy level at, say, room temperature, we would find to our amazement that some would be moving at velocities and with energies corresponding to temperatures close to absolute zero (—273.16°C) and others with energies corresponding to temperatures of thousands, and even tens of thousands, of degrees.

Why the difference? Because the first ones have lost their velocity in collisions and transferred their energy to other particles, while the others have acquired greater velocity through more favourable collisions.

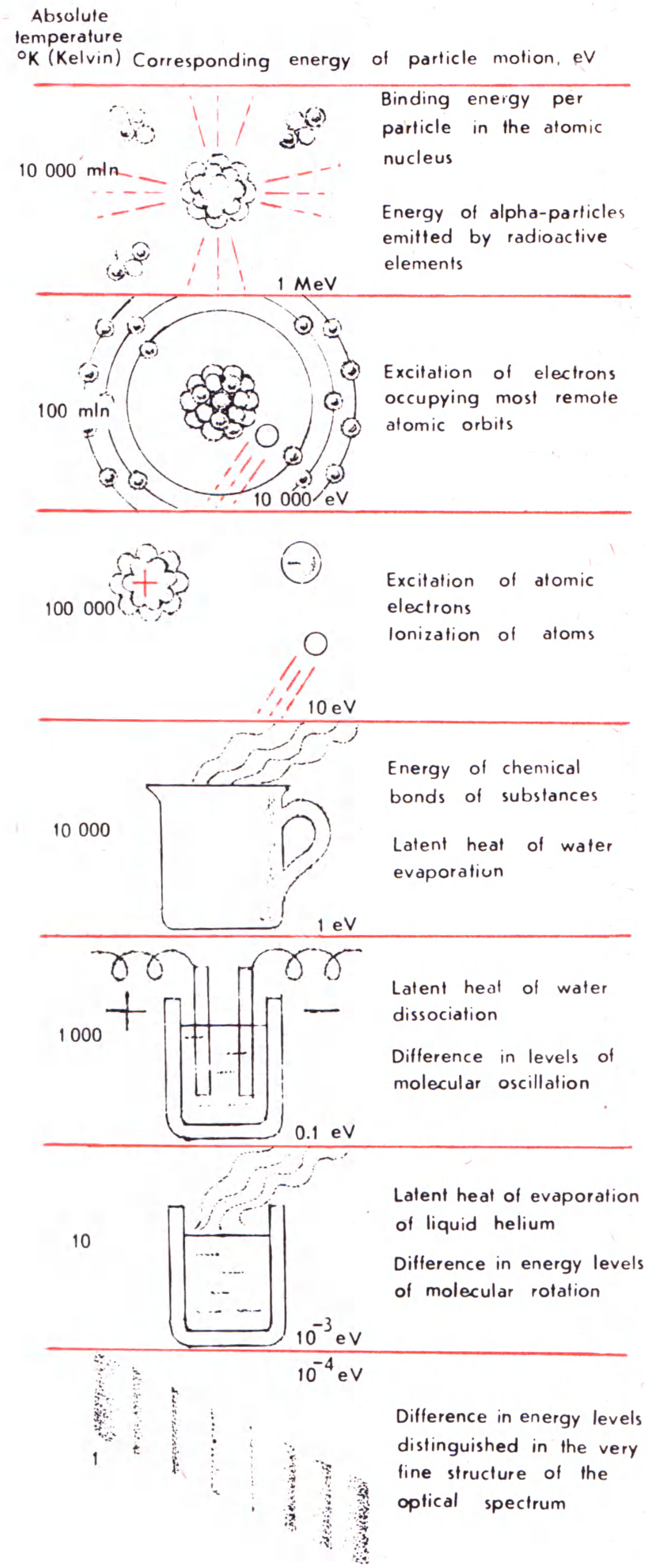
The temperature on the surface of the Sun, that is of the photosphere, for exam-

ple, is 6 000°C. There are more particles there, and they collide more often, with the result that the velocity of their movement is comparatively low. But the temperature of the solar corona is around one million degrees; its density is much lower than that of the photosphere, and particles collide much less often; but then they move with velocities corresponding to such a high temperature.

There is a quite definite quantitative relationship between temperature and energy in all the phenomena encountered in nature. This is shown graphically in our picture. On the thermometer we show the absolute temperatures that are, or may be, found in nature, and on the right some of the physical processes corresponding to these temperatures. The central column gives examples of the energies corresponding to these phenomena and temperatures.

At ordinary room temperature (18°-20°C), an atom of hydrogen, for example, moves with a velocity around 2.2 kilometres per second, which corresponds to an energy of 0.025 to 0.030 electron-volts. But when the energy of hydrogen atoms is raised to 10 000 electron-volts, their velocity rises to 500 kilometres per second, which corresponds to a temperature of 15 million degrees.

A very important observation must be made here, however. The main thing about thermal energy is that it is the energy of particles in random movement. In ordinary gas, for example, molecules move at random in all directions; and as a result of the numerous collisions that occur a certain natural distribution of their velocities comes about. And only when there is such natural random distribution of the direction and velocity of particles are we justified in iden-



Relationship between the kinetic energy of particles (in electron-volts) and the corresponding absolute temperature (in degrees Kelvin)

tifying this movement with the temperature of a gaseous system of particles.

The physical picture is quite different when a flux of particles moves in a vacuum accelerated by a modern accelerator to, say, 1 000 MeV. At that energy in a gas composed of such particles we should seemingly obtain a temperature of ten million million degrees. But that is not what we find, because the movement of these particles takes on an ordered character. They all move in the same direction and rarely collide with one another, so that their motion differs sharply from the random thermal movement that would occur in a gas at such a temperature.

That is why nuclear physicists very seldom operate with concept and magnitudes of temperature, and prefer to employ the concept of energy levels.

The Thermonuclear Reaction

So, continuous heating of a substance sets its particles into more and more energetic motion. Most of its molecules will be broken down into atoms (dissociated) at 10 000 degrees. Atoms lose part or most of their electrons at 100 000 degrees. And, finally, the atomic nucleus disintegrates into protons and neutrons at temperatures exceeding a million million (or ten million million) degrees. That is because all these processes absorb energy, which goes to overcoming the forces of attraction holding together the particles composing the molecules, atoms, or atomic nuclei, and which requires the expenditure of great energy.

In certain circumstances, however, a rise in temperature can lead to the creation of new links or bonds between particles rather than to disruption of their existing links.

You will remember that when the nuclei of various elements are bombarded with protons, for example, the proton can only overcome the repulsive action of the total positive charge of the nucleus when it possesses a very high energy exceeding hundreds of thousands of electron-volts or, what is the same thing, has the enormous velocity corresponding to that energy.

Such energy can be given to a proton, for example, by heating hydrogen to exceptionally high temperatures (measured in tens or hundreds of million degrees). Only then could it approach another proton (or the nucleus of a light element like lithium) close enough to overcome the other's positive charge and so penetrate the realm of the intranuclear forces that would pull it into the centre of the nucleus. For that purpose a deuteron, or an alpha-particle, or several protons, etc., could be used instead of a single proton.

In short, we are concerned here with processes that will end in the combination of the nuclei of light elements into the nuclei of heavier ones, for example, the combination of nuclei of hydrogen to form nuclei of helium.

That can only be done at extremely high temperatures.

If we trace what happens to the energy at this time, we shall obtain a very interesting and instructive picture. To begin with, in order to bring the particles closer together, i.e. to impart the required velocity to them, it is necessary to expend a definite and very large amount of energy. In the case we are considering it is necessary to heat the substance containing the particles to incredibly high temperatures, although only for a certain moment of time. Once the particles come within the field of action of the intranuclear forces, further heating is no longer needed. The movement of the particles will then become faster and faster with no need of outside interference, and energy begins to be released rather than absorbed.

In order to dig up deeply buried treasure one must have a spade of some sort and expend some effort (or energy) on the digging.

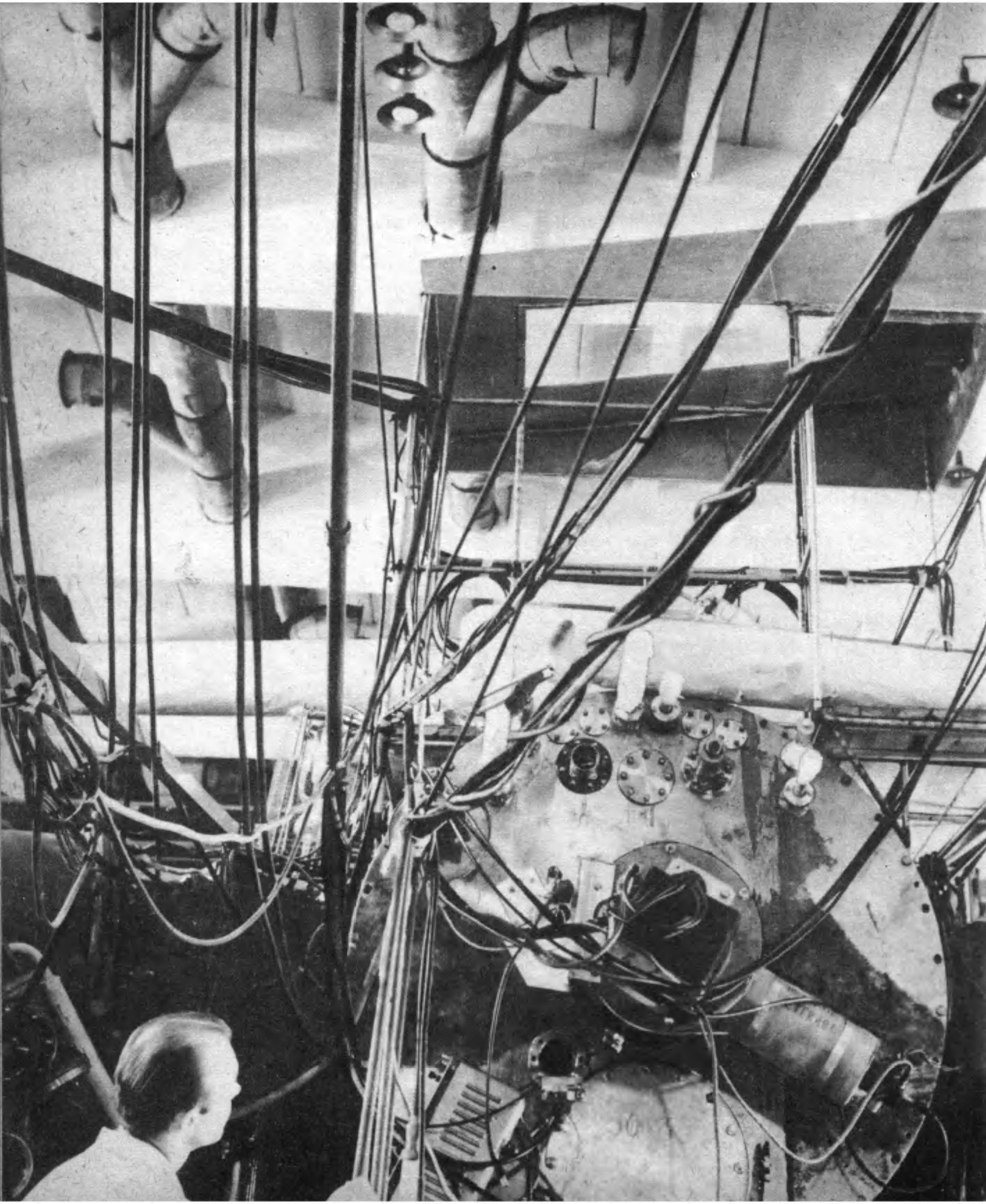
But where are we going to get temperatures that would combine nuclear particles, or the nuclei of light elements, into heavier elements? Do such temperatures exist in nature?

Astronomers say they do. Such temperatures exist in the centre of the Sun and other stars. The main source of the endless radiation of vast amounts of energy from the Sun and stars is *the process of combining (fusing) the nuclei of light elements into heavier ones* or what we call *the thermonuclear reaction.* Not so many years ago man succeeded in producing this reaction on Earth through the explosion of the hydrogen bomb.

From studies of the star nearest to us, the Sun, and the work on creating the hydrogen bomb, it can be taken that the nuclear fusion reaction of light elements best studied at present is the reaction forming helium nuclei. Theoretically several different combinations are possible.

The most important difference between the thermonuclear fusion reaction of the nuclei of light elements and the nuclear fission reaction of the heavy elements is that the latter does not initially require either high temperatures or high pressures. The thermonuclear reaction can only be initiated and maintained at extremely high temperatures of hundreds of millions of degrees, for only at such temperatures do the particles involved acquire the enormous velocities needed to overcome the forces of repulsion between approaching nuclei (which explains why heat is of such great and decisive importance in reactions of this kind). (The Greek word *thermos*, heat, incidentally, gave the name for these reactions 'thermonuclear'.)

And on that note we may end our chapter on 'horrible theories', in order to return to the main line of our story, which is about how scientists arrived first at the theory and then at realizing the idea of liberating the energy hidden in the atom. But we shall have to return to some of these 'horrible theories' more than once before we finish.



Chapter Seven

CONTROLLED NUCLEAR FISSION

Before we get on with our exposition let us look at a very essential question, perhaps the most important one of all.

Why is a chain reaction building up like an avalanche not set off in natural uranium (which is a mixture of the isotopes uranium-234, uranium-235, and uranium-238), even when a large quantity is irradiated by a flux of neutrons of every intensity?

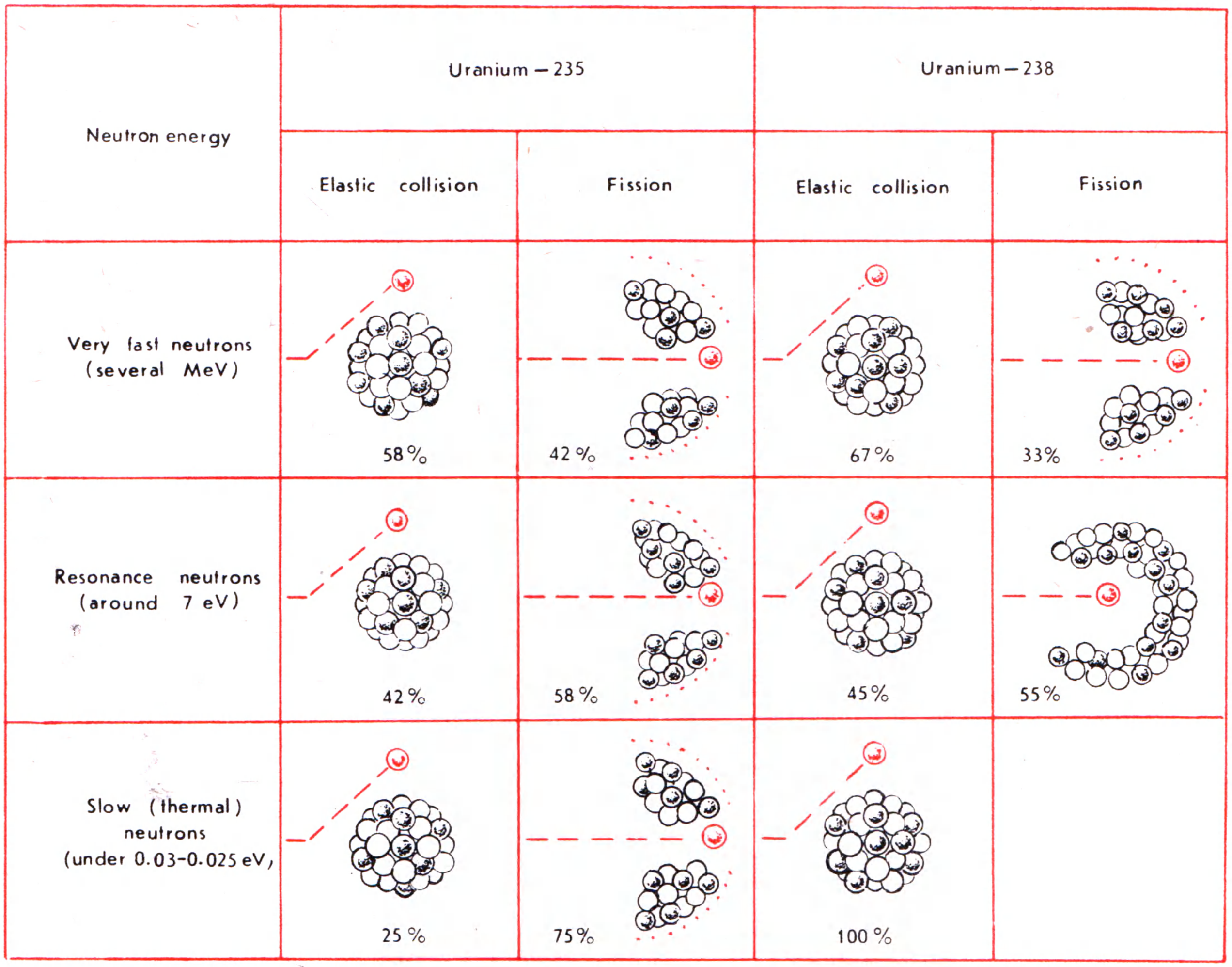
It turned out that the fate of the neutrons penetrating natural uranium was not the same.

Neutrons, like other nuclear particles, move at different velocities depending on their energy. The slowest compare in velocity with the thermal movement of molecules at ordinary room temperatures. Expressed in electron-volts their energy does not exceed 0.03. Neutrons can be slowed down to this velocity only by numerous collisions with the nuclei of other elements; and they are usually referred to as thermal neutrons in contrast to the fast ones emitted from radioactive sources. The ways in which the various neutrons affect a uranium nucleus are shown in the table below.

Some of the fastest neutrons, with energies above one million electron-volts, split not only the nuclei of uranium-235, as already mentioned, but also nuclei of uranium-238.

Now if all the neutrons ejected during the fission of uranium nuclei had an energy exceeding one million electron-volts, it would have been easy to discover how to liberate their intranuclear energy. The fission of uranium-238 and the chain reaction set off by it would have been as easy as with pure uranium-235.

But the energy of most of the neutrons ejected during the nuclear fission of uranium-235 is much below one million electron-volts, so that they do not cause fission of uranium-238.



The effect of neutrons of various energies on nuclei of uranium-235 and uranium-238. The percentage in each box indicates roughly what proportion of neutrons are involved in fission, elastic collision, or capture

The nucleus of uranium-235, however, is particularly easily split by very slow, thermal neutrons with energies much below 0.03 eV.

In the energy band between seven electron-volts and one there is a zone where the nuclei of uranium-238 can completely absorb (or capture) almost any number of neutrons striking a lump of natural uranium. This zone is known as the zone of resonance capture.

Consequently there are neutron velocity bands or energy levels that are specially favourable for the fission of certain uranium isotopes, and others that are less favourable, regions of strong

absorption of neutrons by some uranium nuclei and regions of weak absorption by others.

Obtaining the First Artificial Elements

Let us, however, return to the events that led up to the development of the atomic bomb.

Many scientists had not abandoned the idea that when uranium was bombarded with neutrons, atoms of a superheavy element, even if only one solitary atom, would result from the numerous collisions. And in fact, in 1940, a substance with an atomic number of 93 and an atomic weight of 239 was detected among the fission products of uranium-235.

Careful study of the infinitesimal quantity of this completely new *transuranic* element by the techniques of microchemistry made it possible to revalue the role of uranium-238.

Having absorbed a resonance neutron the nucleus of uranium-238 does not disintegrate but becomes a highly excited artificial isotope, uranium-239 ($_{92}U^{239}$), which is very unstable (with a half-life of 23 minutes), and decays, ejecting an electron, into a new radioactive element with an atomic number of 93 and atomic weight of 239.

Since the planet Uranus is followed in the solar system by Neptune, this element was given the name neptunium ($_{93}Np^{239}$)

$$_{92}U^{238} + {}_0n^1 \rightarrow {}_{92}U^{239} \rightarrow {}_{93}Np^{239} + e^-$$

Two or three days later half of the neptunium thus newly formed decays in turn, also ejecting electrons, and forms another new, but much more stable radioactive element with an atomic number of 94 and atomic weight of 239. This new element was given the name 'plutonium'.

The half-life of plutonium is 24 000 years. It disintegrates, ejecting an alpha-particle, into uranium-235.

$$_{93}Np^{239} \rightarrow {}_{94}Pu^{239} + e^- \rightarrow {}_{92}U^{235} + {}_2He^4$$

But the most important thing about plutonium turned out to be that, like uranium-235, it splits into two parts when hit by either fast or slow neutrons.

Scientists now had two fissile substances, uranium-235 and plutonium.

Naturally, the question then arose which of the two it was easier and more profitable to produce in large quantities. The answer now depended on how the technological problem of their production would be solved.

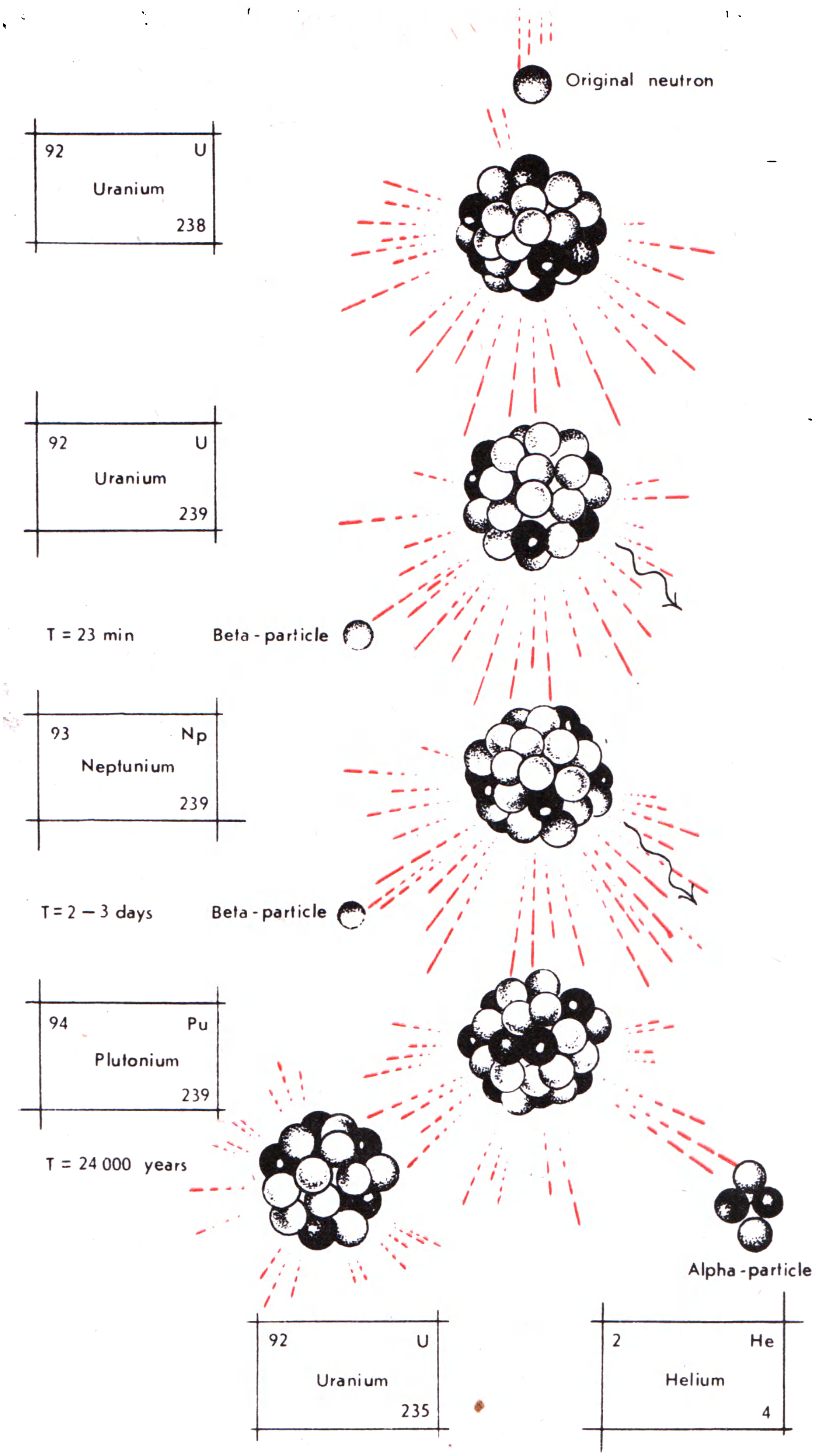
We know what difficulties are involved in separating the isotopes of an element, in this case uranium-235 and uranium-238.

If uranium-238 is exposed to neutron bombardment, it can be turned into plutonium-239 which is much easier to separate from natural uranium, since uranium and plutonium, though near to one another, are completely different chemical elements and can be separated by ordinary chemical techniques.

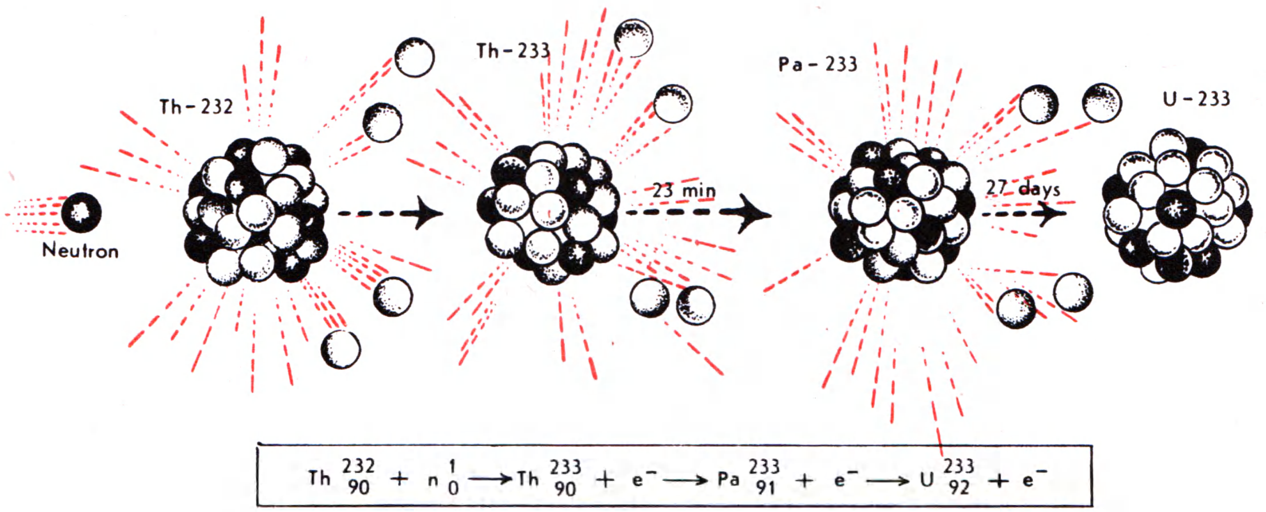
But there is another fissile element, thorium.

Like uranium-238, thorium can only be split by fast neutrons, and therefore cannot be used as nuclear fuel. But, then again, like uranium-238, thorium-232 becomes beta-radioactive after capturing neutrons of lower energy and is transformed after two disintegrations into uranium-233, an isotope not occurring in nature. This isotope, like uranium-235, and plutonium, is easily split by neutrons of any energy. So fuel for nuclear power stations can also be made from thorium.

But in order to employ the second way of producing fissile material, it was necessary to find a source of neutrons powerful enough to turn uranium-238 ra-



Original neutron
92 U
Uranium
238
92 U
Uranium
239
T = 23 min
Beta - particle
93 Np
Neptunium
239
T = 2 — 3 days
Beta - particle
94 Pu
Plutonium
239
T = 24 000 years
Alpha - particle
92 U
Uranium
235
2 He
Helium
4



Having absorbed a neutron, non-fissile thorium-232 becomes the fissile uranium isotope, uranium-233

pidly into plutonium by irradiation and in the quantities required.

Use of the very weak radium-beryllium source was out of the question. It was too feeble even to produce microscopic batches of plutonium.

Neutrons are found in cosmic rays (of which we shall speak later) but only very rarely. And the most powerful accelerators available could not create particles in the required numbers.

So where were they to be obtained?

'Atomic Matches'

There is a French saying along the lines that, in order to jug a hare, you must first have, at least, a cat. In order to start an atomic fire, that is to say, a self-perpetuating chain reaction of the nuclear fission of uranium, one must find an initial, neutron 'spark' somewhere. It had already been established, of course, that charged particles possessing enormous energy penetrated Earth's atmosphere from time to time from outer space. Their energy was of the order of hundreds of thousands of millions, even millions of millions, of electron-volts, and they occasionally collided with molecules and atoms of air; very occasionally they knocked a solitary neutron out of these atoms that might, after wandering around for a certain time, accidentally strike a nucleus of uranium-235 and split it. But that was so chancy a possibility that it could not be depended on.

Therefore, in the experiments that led to the discovery of the uranium fission, the nuclear 'matches' used to ignite it were artificial plutonium-beryllium or radium-beryllium sources. It was necessary to start the fire outside. But for a variety of technical reasons it was not always convenient to do so, especially when it was a matter of initiating a chain reaction with quite large amounts of uranium.

But cannot the atomic nucleus disintegrate of its own accord, without preliminary capture of a neutron? In fact, as first suggested by Niels Bohr, it can be taken that the vibration of the par-

◄ The process of transformation of uranium 238, on capturing a neutron, into plutonium, and 24 000 years later into uranium-235 (T-half-life).

ticles in the nucleus can deform it and as a consequence cause it to split.

Here nature herself unexpectedly came to the aid of the scientists.

The Soviet scientists G. N. Flerov and K. A. Petrzhak, who had been occupied from 1934 to 1940 in investigating the conditions that can give rise to nuclear fission in uranium, and in particular with testing Bohr's hypothesis, had an idea. Since the uranium nucleus is so unstable that it gradually disintegrates, emitting alpha- and beta-particles, it is not beyond the bounds of possibility that some uranium nuclei (one in a thousand million or even in several million million) would spontaneously disintegrate into two portions each of which being supersaturated with surplus neutrons would immediately start to get rid of them.

To prevent their uranium from being hit by stray neutrons coming into the atmosphere with cosmic rays, Flerov and Petrzhak put their samples deep underground in the shafts and tunnels of the Moscow underground railway, which was then just being built. Their experiments fully confirmed their brilliant guess. It turned out that around six or seven of the $2.56 \cdot 10^{21}$ atoms in a gram of uranium spontaneously underwent fission in an hour, for no apparent reason. Thus no artificial outside source of neutrons of any kind was needed in order to induce a chain reaction. The neutrons given off by the spontaneous fission of uranium nuclei could serve as 'matches'.

A Controlled Chain Reaction

The nuclear fission of an atom of uranium-235 into two fragments, nuclei of elements lying in the middle of Mendeleev's Periodic Table, at the same time liberates two or three (on average 2.7) neutrons that are surplus to their needs. And each of these neutrons, don't forget, can cause the nuclear fission of any nucleus of uranium-235 encountered by them, knocking out another two or three (say three) neutrons. These neutrons, in turn, will knock out 9 more, and they will split 27 nuclei of uranium, which will release 81 neutrons, and so on. The number of fissile nuclei will be doubled or tripled with every new generation of fission products and will soon reach astronomic numbers.

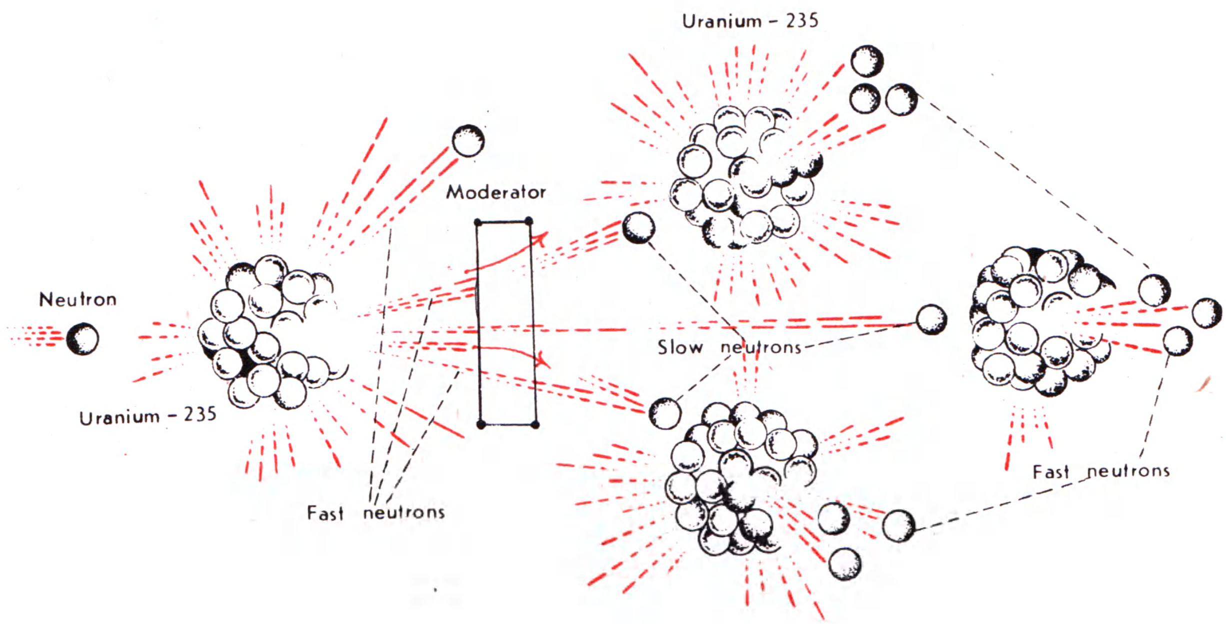
But that is only the ideal, theoretically possible case. In practice, however technically pure uranium is, it always contains impurities that absorb some of the neutrons released by fission.

And in that connection even atoms of the heavy natural isotope U-238 must be considered impurities since, as we know, their nuclei only too readily absorb neutrons, which is why it is impossible to induce a chain reaction 'just like that' in a solid lump of natural uranium of any volume containing 99.3 per cent of this isotope.

So how is it possible to induce a chain reaction?

This is where mathematics, or rather accountancy, comes into its own. If we could 'kindle the fire' by some means or other, that is start a nuclear fission reaction in a bar of uranium and bring it to a certain level (as regards the number of nuclei splitting per second), the reaction would continue at that level if only one of the two or three neutrons liberated at each fission split a nucleus of uranium-235. There is no need even to demonstrate that this quantity, *the multiplication constant* or *factor*, K that is to say, the ratio of the average number of secondary neutrons produced by the fission of new nuclei of uranium or plutonium to the number of primary neutrons obtained from disintegration of nuclei of the preceding generation, will already be greater than unity.

When K is less than unity a chain reaction is impossible, and, if one were



A controlled chain reaction in uranium-235 is possible provided that neutrons are slowed down to thermal velocities (0.03 eV) by means of a moderator

initiated, it would inevitably die out.

But it is not only the multiplication factor that governs the initiation of a chain reaction in uranium.

Nevertheless, how can we start a controlled chain reaction, if the reaction cannot be induced in natural uranium? The overwhelming majority of the neutrons emitted in the course of spontaneous or artificial fission of uranium-235 would be absorbed by uranium-238 long before they had a chance to encounter and split a nucleus of uranium-235.

What must be done is to ensure that more neutrons (of an energy above 7 eV) are slowed up to thermal energy in some other medium before they penetrate the lump of natural uranium, that is to say, to ensure that they cross the zone of resonance energies between one and seven electron-volts (where their absorption by nuclei of uranium-238 is particularly easy) as rapidly as possible, and then return to the bar of uranium. Then nothing remains for the neutrons but to split a few nuclei of uranium-235. And if the amount of natural uranium is sufficiently large a chain reaction must set in.

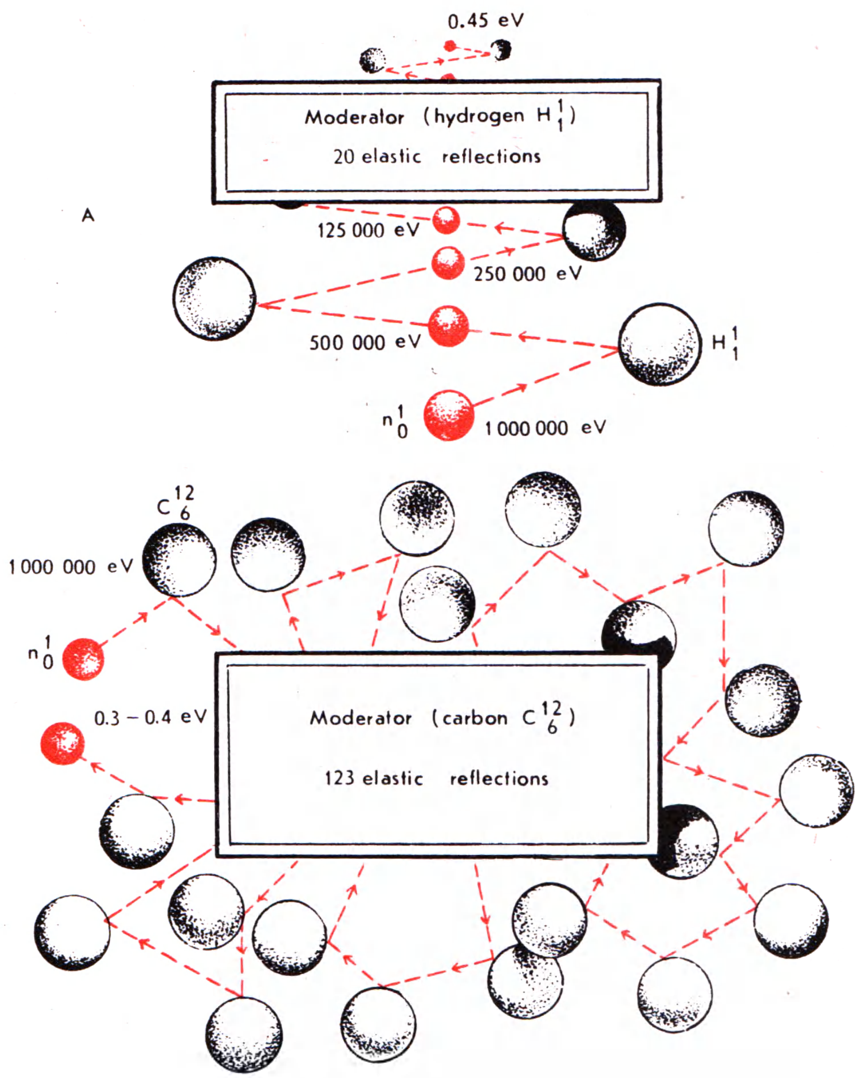
Hence it follows that the problem was to find something that would make it possible to slow down fast neutrons in the shortest possible time to thermal velocities of the order of 0.03 eV without their being absorbed.

So, in order to accomplish successfully this first stage, it was necessary to introduce some *neutron moderator* into the natural uranium.

With that done, how are we to envisage the slowing down of neutrons?

Atoms and a Game of Billiards

We have already mentioned that neutrons may collide with the nuclei of various elements, imparting some of their energy to them, which naturally, in consequence, is diminished.



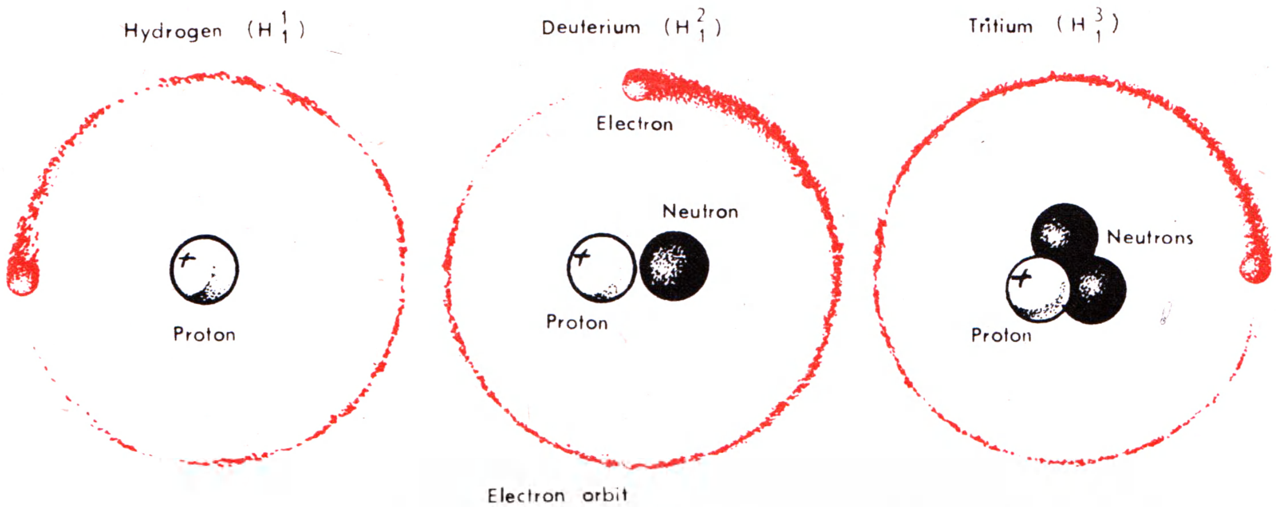
Moderation of neutrons by means of elastic collisions with the nuclei of light elements: *A*—hydrogen; *B*—carbon

Neutrons can be slowed down successfully only when their collision with the nuclei of the substance used as a moderator is elastic, i.e. when the colliding particles recoil from each other. In other words, only materials whose atoms do not in fact capture neutrons should be used as moderators.

From the laws of mechanics it follows that if the velocity of a moving body is reduced by elastic collision with another, fixed or slowly moving body, the greatest energy is lost when the masses of the colliding bodies are equal.

It follows that the nuclei of light atoms, like those of hydrogen whose mass is almost equal to that of a neutron, should be used to slow down or moderate neutrons.

To moderate a neutron ejected during the fission of a uranium nucleus to thermal energy a total of 18 elastic collisions with hydrogen nuclei is required. Then its kinetic energy becomes equal to that of the atoms of the moderator, which (as we know) is determined by its tem-



The various kinds of hydrogen isotope

perature. No moderator, however, is able to reduce the energy of neutrons below the kinetic energy of its own molecules. At room temperature (20°C) the energy of molecules of a gas is between 0.025 and 0.030 eV.

But if a neutron is moderated by carbon nuclei, which are 12 times heavier than it, then, with an equal number of collisions (18), the neutron will lose only 14 per cent of its initial energy. To slow it down to thermal energy 114 collisions will be required, i.e. six times more than when hydrogen is used.

It would therefore seem that ordinary hydrogen would be the best moderator, but, unfortunately, its nuclei easily capture neutrons, becoming as a result nuclei of deuterium (deuterons). Deuterons, however, do not capture neutrons, and require a total of 25 collisions to slow neutrons to thermal velocities.

Helium would be a good moderator; it is light, and has been shown to absorb a comparatively small number of neutrons. But it is a gas, and it is impossible, as with hydrogen, to give it the necessary density, even by compressing it to super-high pressures.

Long research showed hydrogen to be the most suitable and advantageous neutron moderator, but only the hydrogen that is a constituent of ordinary water, and the heavy hydrogen (deuterium) ($_1H^2$) that is a component of so-called heavy water. Of the solids of lowest atomic weight the best moderator is carbon (graphite).

Water That Is Heavier Than Water

Whatever in the world are heavy hydrogen and heavy water?

Back in 1920 Rutherford and Harkins had independently predicted the possible existence of an isotope of hydrogen with a mass double that of ordinary hydrogen. In 1931 an attempt was made to produce this isotope by evaporating a very large quantity of liquid hydrogen, in the expectation that ordinary hydrogen would evaporate quicker than its heavier isotope. And so it turned out. The isotope discovered, heavy hydrogen, was given the name 'deuterium', and its nucleus was called a deuteron.

But this method of producing deuterium proved too complicated and expensive. So, abandoning the idea of evaporating liquid hydrogen, scientists turned to ordinary water. Since atoms of

heavy hydrogen can exist in nature and since water is a compound of oxygen and hydrogen, heavy hydrogen should be a component of molecules of so-called heavy water, and separable from ordinary water by an electric current. Heavy water was found, in fact, to be very minute admixture of ordinary water (0.015 per cent).

Unlike ordinary water (H_2O), a molecule of heavy water (D_2O) contains the heavy isotope of hydrogen, deuterium ($_1H^2$), the nucleus of which consists of a proton and a neutron.

The difference in the properties of ordinary water and heavy water will be clear from the table below.

Heavy water has a deleterious effect on living organisms, and is poisonous in large quantities. Seeds impregnated with it do not germinate, and fish put into it die in a short time.

The production of heavy water was found to be time consuming, complicated, and difficult. To produce one kilogram it is necessary to treat at least six tons of ordinary water, consuming a tremendous amount of electricity. It is therefore often replaced, as a moderator, by graphite of the greatest possible chemical purity.

Critical Mass

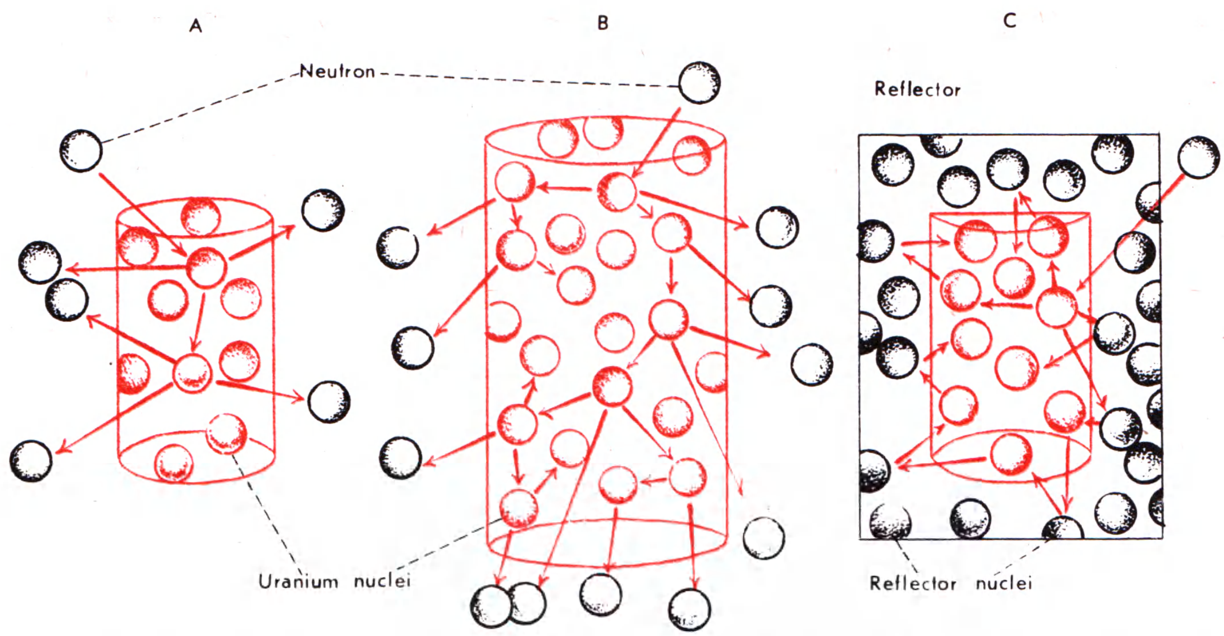
It is well known that no force on earth can ignite a small piece of coal and that it is impossible to keep it burning, while a large heap of coal makes a marvellous fire. The reason for this apparently incomprehensible contradiction is that the chemical reaction of combustion, which takes place at a temperature of 500-600°C, can also be self-sustaining provided the heat released in the process is sufficient to raise neighbouring layers of the fuel continuously to the temperature of combustion. That is only possible when the flow of heat to the combustion zone exceeds the loss of heat through the surface of the still cold fuel. And the smaller the piece of coal, the greater, in relation to its mass, is the surface through which heat is lost, thus for example, surface: volume ratio of a ball 20 centimetres in diameter is only 0.3, while the same ratio for a ball two centimetres in diameter is 3.0, i.e. is ten times greater. And of course, the small ball will lose ten times as much heat to its surroundings as the bigger one.

These losses can be so great that self-sustaining combustion of fuel cannot be achieved; a certain minimum physical volume of fuel is required, which we shall refer to as *critical*.

In order to initiate a self-sustaining chain reaction of the nuclear fission of uranium-235 or plutonium-239, it is necessary that the two or three neutrons ejected from a spontaneously splitting nucleus should always hit neighbouring nuclei of fissile material and split a little more than one nucleus each on the average, and these nuclei in turn should

Properties of Ordinary and Heavy Water

Principal characteristics	Ordinary water	Heavy water
Freezing point, °C	0.0	3.82
Boiling point, °C	100.0	101.42
Maximum density	1.000	1.1071
Temperature corresponding to maximum density, °C	4.0	11.6



A chain reaction is only possible in bars of uranium of definite size. With small bars (*A*) most of the neutrons escape. With bars of large volume (*B*) the majority of neutrons have time to split uranium nuclei. When a reflector is employed a chain reaction can be initiated in a much smaller bar

eject a little more than one neutron, etc., multiplying at a rate equal to a certain value (the multiplication factor K) with each new fission.

But neutrons may not hit the nuclei of neighbouring atoms. The volume of one gram of uranium is 0.053 cm^3 and contains 2.56×10^{21} atoms. And if we calculate the volume of the nuclei of these atoms it comes to only 4.1×10^{-15} cm^3, or one ten-million-millionth of the volume of the bead of uranium, or approximately the space occupied by a ball with a volume of one cubic millimetre compared with the Sun.

In these conditions the neutrons will miss the target hopelessly and fly right out of the piece of uranium, so that a chain reaction will not be started.

But if we take a lump of uranium weighing a score or so of kilograms, i.e. a ball 25 or 30 centimetres in diameter, then the probability of neutrons escaping that have missed and failed to hit uranium nuclei on their path will be reduced to a minimum. Consequently, in order to initiate and maintain a chain fission reaction in a lump of uranium its volume must not be less than a definite volume, or its mass below a definite critical value, the *critical mass*.

But all that reasoning applies only to a lump of one fissile material, uranium-235 or plutonium-239, while a natural uranium contains only 0.7 per cent of the fissile isotope, uranium-235. So, for the neutrons ejected during the nuclear fission of uranium-235 to be absorbed immediately by the nuclei of uranium-238, which constitute the remaining 93.3 per cent of the mass of natural uranium, the lump must be divided into small portions, small cartridges, rods or plates, isolated from each other by a dense mass of some neutron moderator which is necessary in order to ensure that the neutrons escaping from the small bits of uranium (neutrons ejected by the split nuclei of uranium-235) and possessing an energy of 1-2 MeV will hit a neighbouring bit of uranium after they have

been slowed down to a thermal velocity of 0.03 eV, and thereby escaping absorption by the nuclei of uranium-238, will be able to encounter and split nuclei of uranium-235 in the most favourable conditions.

Such an arrangement of small bits of uranium interspersed in a moderator increases the critical mass of the uranium in which a chain fission reaction can be initiated and sustained. Instead of the several kilograms of pure uranium-235 or plutonium-239, the critical mass of natural uranium will thus be several tens of tons and its volume will increase accordingly.

When It's Not a Vice To Be Late

On the basis of these facts and arguments, Fermi and his co-workers proceeded to design an experimental device in which controlled release of nuclear energy could be realized. It was a cumbersome structure built up of blocks of natural uranium and moderator. They called it an atomic pile of nuclear reactor.

In addition to the moderator, the pile needed another component, something that, strange as it may seem, would absorb neutrons.

'What for?', you may ask. 'Surely it was necessary to choose a special moderator that would in no case contain anything at all capable of absorbing neutrons. That is why careful purification of uranium was called for. So, why are neutron-absorbing substances needed now?'

The fact is that it is very difficult to calculate the neutron multiplication factor precisely. And besides, the number of neutrons in a reactor can increase or fall spontaneously for a number of reasons. Finally, for a reactor to begin to operate, it must be started up. All that is connected with a chain of very complicated and delicate interconnections that it is simply impossible to explain at this stage. So let us get on with the main story.

In general, to make it possible to start a chain reaction in a nuclear reactor it must contain amounts of uranium and graphite sufficient to ensure a neutron multiplication factor very slightly larger than unity, i.e. each fission of a nucleus of uranium-235 should produce an average of a little more than one neutron.

In one kilogram of uranium-235 there are around 2.57×10^{24} atoms, and if a chain reaction were started in a block of uranium by only one neutron, the whole astronomical number of atoms would be split in a millionth of a second. So if the chain reaction were not slowed down artificially (i.e. were not controlled) it would terminate in an instantaneous explosion.

Even with all the amazing achievements of present-day electronics, it is impossible to make controls that could respond that rapidly to a variation in the power level of a reactor.

But there were considerations of another order that the operation of a reactor could be quite reliably and comparatively easily controlled, if account was taken of the existence of so-called delayed neutrons.

What kind of neutrons are delayed neutrons? Why, where, and how are they delayed?

To answer that we will have to return once more to the process of nuclear fission of uranium-235 or plutonium.

The point is that the two or three neutrons ejected at each fission are not all produced instantaneously, but at different times. The neutrons that are ejected first are the instantaneous or prompt neutrons which constitute about 99 per cent of the total number.

Their ejection takes place not later than 10^{-12} second after the moment a

neutron is captured by a uranium nucleus. If only prompt neutrons existed, there would have been no question for a long time of control of chain reactions in fissile materials.

Fortunately, however, the remaining neutrons are emitted by the fission fragments, and their escape is delayed by anything from 0.0001 second to several minutes after the prompt neutrons. Therefore, even if a reactor were shut down instantly by introducing a substance with a very high neutron-absorbing power, it would still be possible to detect the emission of neutrons produced by fission products.

It was these delayed neutrons that gave the idea that it was possible to control a chain reaction, since the multiplication factor could be kept exactly at unity only through them.

To make this clear, let us consider an example.

Let us take the mean life of delayed neutrons as about 10 seconds. Then, the mean effective life of the whole aggregate of neutrons in the fissile uranium must increase greatly and will be approximately 0.1-1.0 second.

With such a neutron life, it becomes possible to control a reactor reliably not merely by means of some automatic device, but also by hand.

We have already mentioned that certain substances like boron and cadmium greedily capture neutrons. So if a certain number of long flat rods coated on both sides with some such neutron-absorbing substance are put into a reactor during its assembly, then, even if the amount of uranium exceeds the critical mass, a chain reaction will not start because the neutron multiplication factor will still be smaller than unity. Almost all neutrons will be 'swallowed up' by the atoms of cadmium or boron. And to start the reactor up, it will be necessary to withdraw the absorbing rods from it one after another. At some moment the neutron multiplication factor will reach unity, and then it will slightly exceed it by, say, 0.001. But an instantaneous explosion will not occur because the neutron multiplication factor will rise not because of the principal, fast neutrons (for which K will still be smaller than unity), but mainly on account of the delayed neutrons. As a result the reactor's power will increase about 10 000 times, not in a millionth of a second but in 0.1-1.0 second, or even longer period.

Thus, by withdrawing the control rods a certain distance any desired power level can be set quite accurately from zero to the maximum designed capacity, and at each such level it will be possible to bring the multiplication factor (of the fast, and the delayed neutrons) to unity. And with automatic devices to regulate the withdrawal of the control rods it is not difficult to maintain the multiplication factor with an absolute accuracy.

As soon as the power of a reactor exceeds the preset level, an automatic device pushes the control rods a little deeper into the reactor. More neutrons will be absorbed as a result, and the multiplication factor will again drop to unity.

Now we have to look into another very important problem that particularly interested the first designers of atomic reactors.

What happens to the neutrons ejected by the fissile nuclei or uranium-235? Some of them escape to the outside, some split the next nuclei, and some are captured by uranium-238 and impurities. But if the capture of neutrons by the nuclei of impurities is harmful so that we try to reduce such capture to zero, can we say the same about neutron capture by the nuclei of uranium-238?

Of course not. For do not forget that, under the action of neutrons, these nuclei

form plutonium, a new, artificial fissile material. A little earlier, we even posed the question of what source of neutron should be available in order to produce plutonium in sufficiently large quantities. This source had now been found.

A nuclear reactor is simultaneously a source of energy and a kind of plutonium factory.

It was this side of the problem that most interested the people designing the first nuclear reactor, since they were looking for methods of producing the materials for an atomic bomb. They found the source of neutrons needed for this in the nuclear reactor.

And that perhaps was all that needed to be known beforehand in order to kindle the world's first 'atomic bonfire'. Its power had been limited in advance to a low value but the scientists were dealing with an unknown but terrible force, and it was therefore necessary to secure themselves against it in advance, for if all their preliminary reasoning and calculations were erroneous, the nuclear reaction would prove uncontrollable, and the reactor an atomic bomb exploded deliberately and carelessly in the laboratory.

A 'Mirror' For Neutrons

If, when a nuclear reactor was being built, its power and other properties depended solely on the critical mass of the fissile material being used, the quantity of uranium required would be several dozen tons, possibly hundreds, with corresponding dimensions for the whole structure. Therefore, before carrying out the idea of building a nuclear reactor, scientists were compelled to concern themselves with the following question. In what conditions can the mass of fissile material, pure uranium-235 and natural uranium (uranium-238) and, at the same time, the size of the reactor be reduced to the minimum possible? And, in particular, would it be possible to find some way of drastically reducing the number of neutrons lost irretrievably from the mass of fissile material, without encountering on their way nuclei of uranium-235 waiting to be split?

For as the number of nuclei of uranium-235 splitting increases the number of neutrons escaping from the reactor will rise continuously until a state of equilibrium sets in, at which the increase in the number of neutrons arising from nuclear fission fully compensates the number escaping from the reactor.

The number of fissions per unit time will then reach the limiting value, i.e. the reactor will reach its operating capacity.

Naturally, the smaller the reactor, the sooner such equilibrium sets in, and the lower its capacity will be. In a very small reactor the chain reaction may fail to start at all, for neutrons need only cover a comparatively small distance to escape, and will have no time to encounter nuclei of uranium-235.

But what if steps were taken to return the escaping neutrons? It would then be possible to reduce the size of the reactor considerably without affecting its capacity.

It was achieved by surrounding the reactor with a quite thick shell of a substance like graphite that is a good reflector of neutrons. A reflector is the same as a moderator for after colliding with its nuclei neutrons may also be reflected backward.

After being reflected many times by collisions with the nuclei of the reflector, most neutrons will be directed back into the reactor and fewer, consequently, will be lost; the dimensions of the reactor can then be reduced considerably.

A 'Bonfire' In a Laboratory

On 2 December 1942, in Chicago (USA) a nuclear chain reaction was started for the first time in the world in a pile built of uranium rods separated by graphite bricks. The main 'dramatic persone' was the neutron, slowed down to thermal velocity through multiple collisions with nuclei of graphite.

To prevent surprises, strips coated on both sides with a layer of cadmium were inserted into the pile during its construction. And to be on the safe side, enough cadmium was applied to the strips to capture all the neutrons formed through fission of the uranium.

The pile was assembled in the following way.

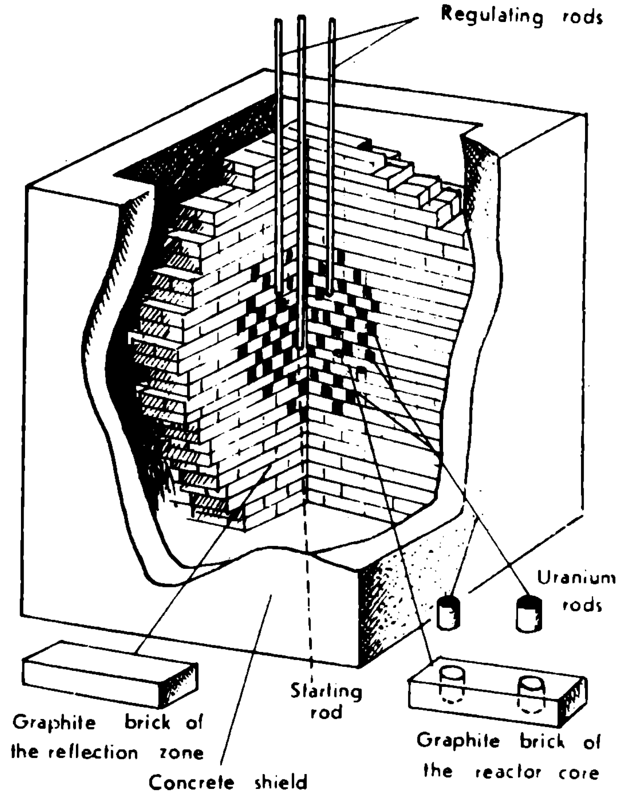
A sort of well with solid walls and a bottom about 60 centimetres thick was built from bricks of graphite around the future reactor. This dense envelope or shell was to serve as a neutron reflector.

Neutrons that for some reason or other escaped from the reactor, without accomplishing the task assigned to them, of splitting neighbouring nuclei of uranium-235, would be reflected back into the reactor from this solid layer of carbon.

Then, layers of graphite brick were built up inside the reactor, alternate ones containing bricks with two slots in them in which rods of uranium clad in aluminium jackets were inserted. Each rod weighed about 2.5 kilograms.

In the resulting cubic lattice each rod of uranium was isolated from the next one by a layer of graphite equal to the thickness of a solid graphite brick. A schematic diagram of this reactor is shown in our drawing.

In addition to channels into which cadmium-coated strips were to be inserted, a great number of holes were left in the pile, running to various depths, in which sensitive counters were placed, the purpose of which was to detect the appearance, and then a rise in the signs that a chain reaction has been started in the reactor (radioactive particles, gamma-radiation and neutrons).



The internal arrangement of the first uranium-graphite nuclear reactor

As the number of uranium rods was increased, a cadmium strip, originally inserted to its full depth, was gradually withdrawn.

Finally, after the 50th layer of graphite bricks, containing lumps of uranium, was laid, and the cadmium strip was fully withdrawn, a controlled chain reaction began, as expected. After that several layers of graphite bricks were laid on the top to serve as a neutron reflector, and long and careful study of this new physical reaction was begun.

The first atomic pile was quite large, $9 \times 6.3 \times 9.6$ metres and weighed more than 1 400 tons. It contained about 52 tons of uranium, of which ten tons were made up into 3 200 rods of pure (metallic) uranium clad in soldered aluminium, and the remainder into 14 500 cartridges filled with uranium oxide, since sufficient metallic uranium was not then yet available to build the whole pile from it. The moderator and reflector took about 472 tons of graphite.

Control and regulation of the reaction was achieved by inserting and withdrawing five cadmium-plated bronze strips each about 5.2 metres long.

This first nuclear reactor was far from perfect. Its thermal capacity at first was so small as to be absurd—only about one-twentieth of a watt, a mere fleabite. Later its thermal capacity was raised to 200 watts.

The reactor had no forced-circulation cooling system, and the energy produced was not utilized. And finally, it had no radiation shielding system. But that did not bother the scientists.

All the theoretical calculations and predictions, relating not only to the design of this particular reactor, but also to the whole edifice of nuclear physics built up with such difficulty, would be shattered or, on the contrary, would be visibly and indisputably substantiated, depending on how the installation worked. It was an experimental check of all the preceding nearly half-century of work by physicists, and the first attempt to obtain real energy from a nuclear reaction.

A new age was born—the age of atomic energy.

As to the reactor itself, the predictions concerning the processes taking place in it were proved. Everything went just as the scientists expected, but not always smoothly, and there were temporary failures and accidents that soon dampened the scientists' triumph.

The starting-up of the first nuclear reactor, as was to be expected, cleared many ways along each of which very strong teams of scientists now set off. It was difficult to foresee when they met one another here and there, who had gone further, who had fallen behind, where it was necessary to send reinforcements, and where to get them, and so on.

In the capitalist countries of the West, the biggest detachment of scientists was engaged primarily on the production of the atomic fuel (uranium-235 and plutonium) needed to produce the most terrible weapon of modern times, the atomic bomb.

The Atomic Bomb

We have already mentioned that the nuclear fission of uranium-235 takes place in an instant of time equal to about a hundred millionth of a second. If each fission is accompanied with the ejection of two or three neutrons, each in turn causing the fission of a new nucleus, all the 2.57×10^{24} atoms in a kilogram of uranium-235 will undergo fission in a millionth of a second. An explosion of tremendous destructive power will take place, liberating energy equal to that released by the explosion of 2 500-3 000 tons of the most powerful chemical explosive.

But such an explosion can only take place if the amount of uranium-235 involved is equal to or exceeds the critical mass. And for a chain reaction to start, it is also necessary that the lump of uranium-235, in addition to being of critical mass, should be as compact as possible (possessing maximum volume and minimum surface). When the atomic bomb was being built it proved very difficult to establish this shape and a great risk was run. For any of the cal-

culations might be incorrect, and the penalty for a mistake was extreme—an atomic explosion.

One of the possible designs of an atomic bomb is illustrated in our drawing. The critical amount of uranium (or even a little more) is divided into two hemispheres, the mass of each being made deliberately smaller than the critical mass. The two hemispheres are positioned sufficiently far apart so that a chain reaction cannot develop in the bomb, and it is quite safe.

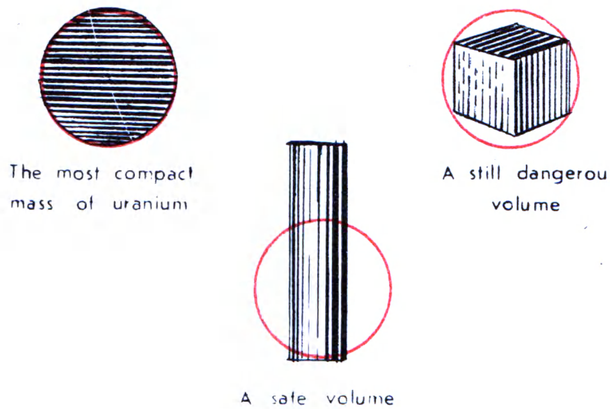
Then, if the two hemispheres are brought together very quickly, if one is fired against the other, for example, so that they form a piece of uranium that exceeds the critical mass, a self-sustaining nuclear chain reaction will be initiated and an explosion occur.

The critical mass of each of the hemispheres can be reduced if they are encased in a shell that reflects neutrons back into the uranium.

The two hemispheres must be brought together quickly because the chain reaction in the whole piece of uranium begins a tiny fraction of a second before they come into actual contact, and the force of the explosion could scatter pieces of uranium before nuclear fission began in them. Scattering is prevented by the dense, heavy casing of the bomb. According to figures published in the Press an atomic bomb can contain as little as a few kilograms of uranium-235 or plutonium-239.

Once More About Neutrons

So far, in speaking about the capture or absorption of neutrons by the nuclei of various elements, like those of uranium-238, we have deliberately simplified the true picture of the phenomenon. In actual fact the process is amazingly complicated, we might even say 'cunning', in character.



The best shape for starting a nuclear chain reaction in a certain volume of uranium is that of a ball or sphere

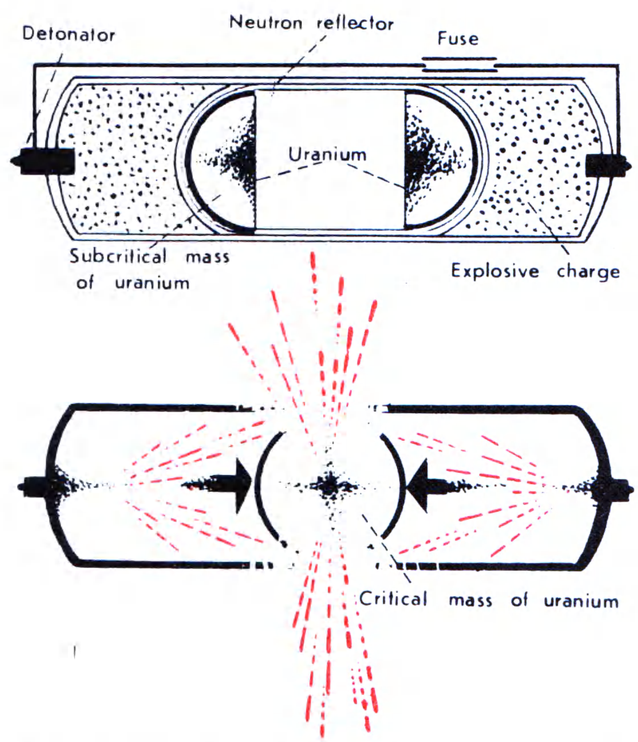


Diagram of the arrangement of an atomic bomb. When the two hemispherical pieces of uranium, each of subcritical mass, are fired into each other, they unite instantly to form a critical mass of the most effective shape (a sphere)

So where do neutrons get their unusual properties and capacities, so different from those of other nuclear particles (although the latter also have more than their own share of amazing properties)?

We have already mentioned that any particle of matter, like the light quantum, possesses both the properties of a wave and of a corpuscle. And since the mass of a neutron is infinitesimally small compared with that of any other, even ultramicroscopic, body, its wavelength becomes quite an appreciable property in the phenomena of the microworld, and begins to show as its velocity is slowed down.

Neutrons with high velocities (energies) have such short wavelengths that their wave character does not show in practice. But the velocity of a neutron can be slowed down to such an extent that it completely loses its character of a particle and behaves like a true light wave, with the capacity even to be reflected from a well-polished surface, to be diffracted when passing from one medium to another, and so on.

For that reason very obvious difficulties arise when we try to determine the real size of a neutron, for it depends on the velocity of the particle concerned. The diameter of an atom, for example, is between $2 \cdot 10^{-8}$ and $4 \cdot 10^{-8}$ centimetres; the diameter of the atomic nucleus is much smaller, about 10^{-13} centimetres; finally the diameter of a proton is barely $2 \cdot 10^{-14}$ centimetres. But the diameter of a thermal neutron with an energy of 0.03 electron-volt is $2 \cdot 10^{-8}$ centimetres, that is to say, is the same as that of a whole atom. And there are other paradoxes just as puzzling.

The neutron turns out to be tens of thousands of times larger than the diameter of a nucleus, which itself contains not one, but many neutrons. Strange, but a fact!

This incredible capacity of particles 'that don't exist' in certain conditions to swell, as it were, depends on the whole solely on their wave properties. So it would be more correct to think of a neutron of such low energy not as a particle but as a wave $2 \cdot 10^{-8}$ centimetres long. Possessing such a wavelength the neutron behaves as if its size corresponded to the diameter of an atom.

But when a neutron moves at very high velocity its wavelength is short, and it then manifests the properties of a particle; and the greater the velocity, as we already know, the greater is the energy. Therefore, in order to remain within the atomic nucleus a neutron must have a minimum energy of 50 MeV, and energy (velocity) at which its wavelength is equal to or less than 10^{-13} centimetres.

We might have been able to dispense with these complications perhaps, but then much of what we have explained earlier, and more particularly what we are going to speak about further on, would seem contradictory and strange. But if we bear in mind the dual character of the neutron, its capacity either to be more like a particle (and consequently to shrink in size) or to be more like a wave (and consequently to seem to swell), depending on its velocity (energy), these contradictions and oddities will not seem so unnatural each time, or something purposely thought up by scientists in order to get over difficulties they had encountered.

But difficulties arise at every step since all the main nuclear reactions involve collisions either of fast or slow particles or of quanta of radiation with the atomic nuclei of other substances.

Consequently, their purely nuclear properties must be defined by a certain magnitude that gives an idea of the probability of their mutual collision, i.e. the

size of the *cross-section of a nucleus* or *nuclear particle*.

This magnitude, although not employed in ordinary physics, as we have just seen from the example of the neutron, is quite indispensable in nuclear physics.

Imagine that you are out hunting and a flock of birds flies above your head. The probability of hitting one of them with a shotgun is proportional to the size of the target, or rather, to the cross-section (area) of the target, at the moment you shoot. Naturally the chances of hitting a kite are much greater than of hitting, say, a sparrow. But if the birds were the size of elephants, the results of your shooting would be much better. And what is more, if at the moment of hitting the target the shot increased to the size of a football, then your chances would be even better.

In other words the possibility of an encounter between shot and bird is directly proportional to the size of the target and the gauge of the gun (or shot) used. And the chances would be increased or reduced if, by some magic, both shot and target could, when necessary, grow in size at the same time or separately.

Something similar happens when a flux of particles is directed at a substance. Some of them collide at once with atoms of the material being irradiated, and others fly past. If it were possible in some way to increase the size of the particle 'projectiles' (which can be done with neutrons by slowing them down) the chances of a collision would be greatly increased, and vice versa.

Thus the cross-section of particles and atoms is a measure of the probability of their colliding. A larger cross-section corresponds to a greater probability of collision.

The term 'cross-section' (or simply 'section') proved to be very convenient for describing a whole number of phenomena encountered in nuclear physics. When, for example, we say that uranium-235 has a certain fission cross-section we refer, of course, to the probability of its fission. When a beam of neutrons is directed onto an ideally thin film of uranium some of them will collide with its nuclei and induce fission. But when we speak of the cross-section of a nucleus in the event of elastic collision, we mean the probability of collisions that do not involve absorption and in which the particles recoil from each other like ideal billiard balls.

In these circumstances what should the cross-section of an atomic nucleus be?

In most cases the nucleus behaves as though its diameter were around 10^{-13} centimetres, or its cross-section around 10^{-24} square centimetres. This value is taken as the unit cross-section and is referred to as a *barn*. The barn varies in magnitude, increasing from light to heavy elements, and also according to the nature of the chain reaction, and the type and energy (velocity) of the bombarding particles (which is most important, and about which we have already spoken).

A cross-section of one barn is generally considered to be large.

What cross-sections of atoms do we have to deal with in nuclear reactions?

The cross-sections of most interest to us are those of fissionable materials, in particular, of uranium-235, plutonium-239, and uranium-233. When the nucleus of uranium-235 splits into two fragments, the surplus neutrons emitted by the fragments have quite high energies, 2 MeV on the average.

The fission cross-section of uranium-235 nuclei is relatively small for such high-energy neutrons; the bulk of them fly past and do not collide with the nuclei. But the cross-section of these same nuclei proves to be quite large in relation to slow neutrons moving at ther-

mal velocities around 0.03 eV; and it is difficult for such neutrons to avoid colliding with nuclei.

That is why, when one wants to induce a chain reaction in uranium-235, it is best to slow neutrons down, which we do by forcing fast ones to collide with the nuclei of substances that produce elastic collisions. But in arranging such artificial collisions we have to be sure that the neutrons do not become involved in some process of absorption. In other words, the material used as a moderator must have the largest possible cross-section for elastic collisions and the smallest possible section for the capture and absorption of neutrons.

Here we must emphasize the importance of extreme purity in the materials used as moderators. If the carbon used as a moderator is 'contaminated' by as little as ten parts of boron in a million, for example, the number of neutrons absorbed by the boron impurity will be the same as the number absorbed by all the carbon.

The conflict between useful and harmful employment of neutrons is a subject of constant concern to scientists.

If we plot a curve representing the cross-section of uranium-238 against neutron energy we shall see that it has a peak or *resonance* somewhere in the vicinity of 7 eV, between the energy of neutrons emitted during the fission of uranium-235 (2 MeV) and the energy required to ensure the easiest fission of uranium-235 (0.03 eV). But if we try simply to slow down neutrons we will inevitably suffer great losses when approaching and passing the zone of resonance absorption of neutrons in uranium-238.

And there is something else.

When nuclear fuel undergoes fission the elements formed from it occupy places in the middle of the Periodic Table, and some of these have a small neutron-absorption cross-section while others, on the contrary, have a large one and act as parasites reducing the number of useful neutrons.

Therefore, in order to avoid 'slagging' of nuclear fuel, fission products must be removed from it as rapidly as possible; but that, unfortunately, is not always possible.

The Road to 'Transurania'

At the beginning of this chapter we spoke, very briefly, about a most amazing and, incidentally very long delusion that had the result of delaying one of the greatest discoveries of our age—nuclear fission of uranium by neutron bombardment—by at least five years. Knowing what happened afterwards, of course, we are perhaps justified in saying that every cloud has a silver lining.

Fermi's inspiration of genius, which we have only mentioned in passing, nevertheless led to the discovery in 1940, by American scientists, of real transuranic elements, neptunium-239 (No. 93) and plutonium-239 (No. 94).

Miracles are called miracles because they happen so seldom and never in succession, so that, naturally, there has never been a second miracle of similar scale and consequences. Parallel with the work of tremendous scope devoted to the production of fissile materials, the efforts of scientists in the USA (where, in the end, not only all the work on obtaining transuranic elements had been transferred but also the majority of its initiators in Fermi's circle) were concentrated on bombarding heavy elements, including the first transuranic ones, with heavy particles like the nuclei of deuterium, alpha-particles, and multi-charged ions in powerful, specially designed accelerators.

Since 1940, 12 artificial transuranic elements have been produced altogether,

Atomic number	Name	Symbol	Half-life
93	Neptunium	Np 239	2.35 days
94	Plutonium	Pu 238	86.4 years
95	Americium	Am 241	458 years
96	Curium	Cm 242	162.5 days
97	Berkelium	Bk 243	4.5 hours
98	Californium	Cf 245	44 minutes
99	Einsteinium	Es 253	20 days
100	Fermium	Fm 255	22 hours
101	Mendelevium	Md 256	1.5 hours
102	(Nobelium?)	(No) 254	3 seconds
103	Lawrencium	Lw 257	8 seconds
104	Kurchatovium	(?) 260	0.3 second

about one every two years. These dozen elements occupy places 93 to 104 in the Mendeleev Periodic Table, and their mass numbers lie between 231 and 260. Two of them, plutonium and neptunium (which transforms into plutonium), are now produced by the ton. Five of the others have been obtained in appreciable quantities, but atoms of the rest have literally been obtained one at a time.

The new elements were given the following names, in the order of their atomic numbers (see above).

Each of them has several isotopes, and a total of more than a hundred have been produced and studied. All were produced, crudely speaking by 'penning' one or two protons within the nucleus of an existing element by means of a particle accelerator, although the same could be done by adding one or more neutrons to the nucleus.

The discovery of nuclear fission for many years outshone all the other achievements of nuclear physics, including the work on creating transuranic elements.

The first few transuranic elements were made by bombarding a target made of another transuranic element with a smaller atomic weight. The first few atoms of the element 95, for instance, resulted from the irradiation of plutonium with a flux of neutrons. And only several years later did scientists succeed in producing a more appreciable quantity of this element, now by irradiating plutonium in a nuclear reactor. Having captured two neutrons in succession, the plutonium nucleus emits an electron and turns into the nucleus of an isotope of americium.

The reaction can be written as follows:

$$ {}_{94}Pu^{239} + {}_{0}n^{1} \rightarrow {}_{94}Pu^{240} + {}_{0}n^{1} \rightarrow {}_{94}Pu^{241} \rightarrow \rightarrow {}_{95}Am^{241} + e^{-} $$

Element 96 (curium), element 97 (berkelium), element 98 (californium), and element 101 (mendelevium) were first obtained by bombarding plutonium-239, americium-241, and curium-242 with nuclei of helium. In each case the helium nucleus, consisting of two protons and two neutrons, fused with the heavy nucleus. In the course of the fusion the positive charge of the heavy nucleus was increased by two units and one or two neutrons vanished.

Element 99 (einsteinium) and element 100 (fermium) were detected at an altitude of 16 kilometres in the radioactive cloud formed after the first thermonuclear explosion carried out by the USA on an atoll in the South Pacific.

Research showed that something quite unusual (from the scientific point of

view) had happened as a result of the thermonuclear explosion. The nucleus of uranium-238, which was a constituent of the explosive device, proved capable of capturing 17 neutrons at once! As a result an extremely heavy isotope of uranium with an atomic weight of 255 (instead of 238) was formed that turned successively, in the course of subsequent radioactive disintegration, into heavy transuranic elements, including elements 99 and 100.

Other methods were later developed enabling these elements to be produced in a nuclear reactor that created a very dense flux of neutrons.

After a certain amount of einsteinium had been obtained it was bombarded with helium nuclei in a cyclotron. The result was the production of atoms of element 101, which, since it began the second century of chemical elements in the Periodic Table, was named mendelevium in honour of the creator of the Table. The nuclear reaction that formed it can be written as follows:

$$_{99}Es^{253} + _{2}He^{4} \rightarrow _{101}Md^{256} + _{0}n^{1}$$

One-half of mendelevium decays in half an hour, turning into an isotope of fermium, which in turn disintegrates at once into two fragments. It took long work of brain-racking complexity to identify this element (which we lack the space to tell about, even in passing) and to obtain exactly 17 atoms of it!

With element 102 a whole series of curious things happened. After its discovery had been announced by workers at the Nobel Institute of Physics in Stockholm in 1956, and later in the USA in 1958, it was found that both reports had been premature. The element had hastily been called nobelium, then was known just as No. 102, but has now been renamed nobelium. One of its isotopes was identified by a group of physicists in Dubna in the USSR while bombarding curium with carbon ions. The atomic weight of this isotope is 253 and its halflife about three seconds.

Element 103 was only produced in April 1961 through bombarding a target of californium with boron ions in a linear accelerator. Since the atomic number of californium is 98 and that of boron 5, the researchers supposed that when the two elements fused a new element with an atomic number of 103 should appear. And although only 3.0 micrograms of californium were available, a quantity only visible under a microscope, they succeeded in recording the formation of the new element in the course of the following reaction:

$$_{98}Cf^{252} + _{5}B^{10} \rightarrow _{103}X^{257} + 5_{0}n^{1}$$

That is to say, the reaction taking place in the target emitted five neutrons simultaneously!

This element was called lawrencium in honour of the inventor of the first cyclotron, the Nobel prize-winner E. O. Lawrence.

The credit for creating element 104 belongs to a team of Soviet physicists working under the leadership of G. N. Flerov, Corresponding Member of the USSR Academy of Sciences. This new element was obtained in a unique accelerator of multicharged ions that gave a flux of particles 100 times denser than had been obtained with any other accelerator. Element 104 with an atomic weight of 260 was only identified by means of an original technique of direct separation of the products of the nuclear interaction, because its half-life proved to be only three-tenths of a second.

After days and days of experiments 150 nuclei of the element were identified, which can be considered a great achievement.

But much more important was the fact that element 104 is very different

in its chemical properties from the other transuranic elements and is chemically an analogue of hafnium (No. 72), and consequently begins both a new group of super-heavy elements with specific chemical properties (which confirms the correctness of the periodic system) and a new field of transuranic elements.

To obtain element 104 a target of plutonium was irradiated with a flux of neon ions, which resulted in the formation of a highly excited nucleus with an atomic weight of 264. In one case in a thousand million it ejects four neutrons and so achieves an unexcited state with an atomic weight of 260. It was proposed to call the new element kurchatovium in honour of the late Soviet physicist I. V. Kurchatov.

From the pattern of the Periodic Table and from the chemical properties of some of the transuranic elements already investigated scientists suppose it possible to produce even heavier ones up to element 126, provided their half-life is sufficiently long to give time for chemical identification.

Instead of the helium nuclei, heavier bombarding particles—nitrogen, neon, carbon and even heavier ions—will need to be used to discover transuranic elements. And for that purpose high-energy ion accelerators have been built in several countries.

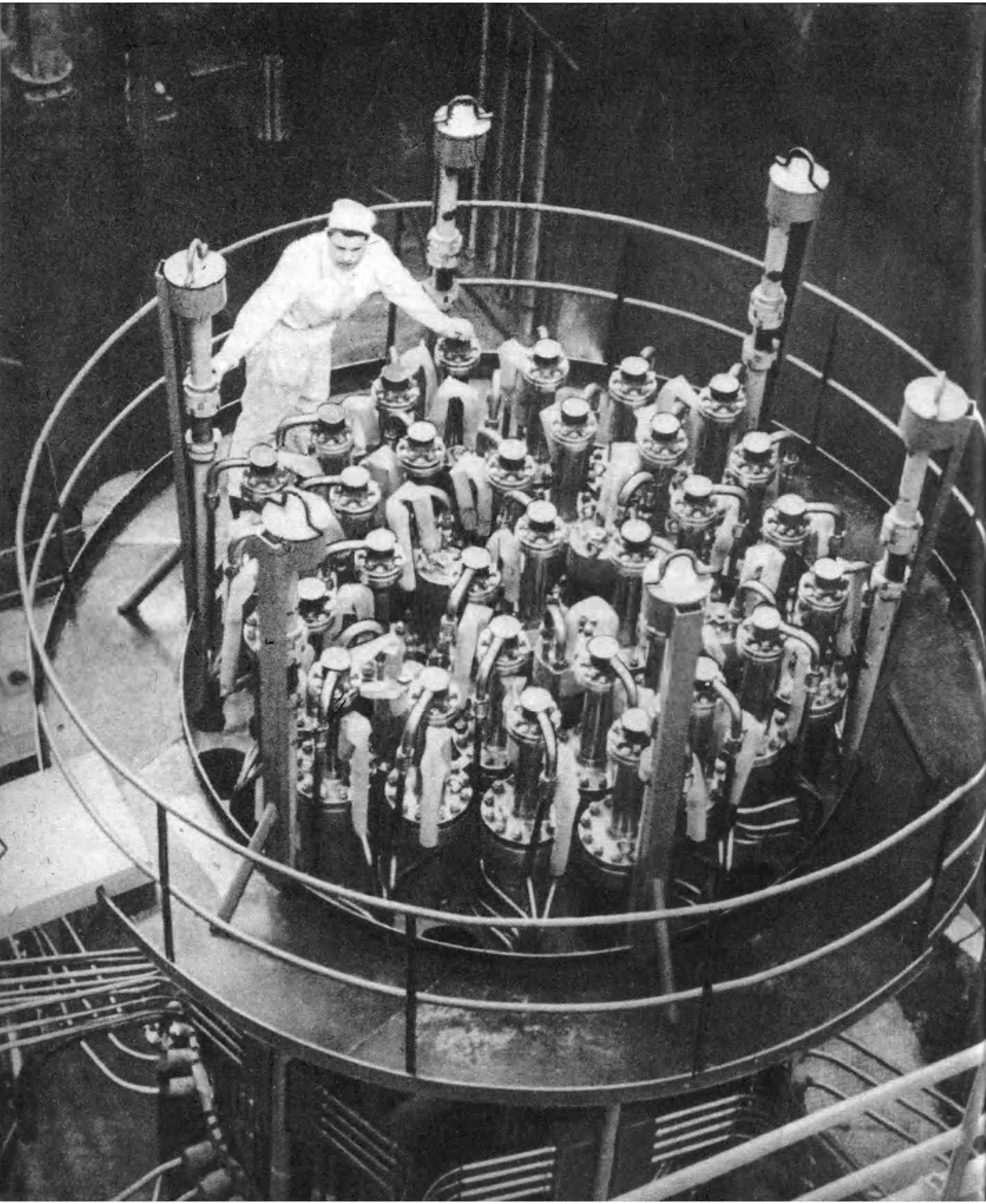
You may well ask: what is the good of trying to produce new elements, especially short-lived ones? And what earthy use can be envisaged for them in any field of nuclear engineering?

At the beginning of our book we described three families of radioactive elements, descendants of uranium-238, thorium-232, and actinium-235. The fact that the families formed by them are in the process of intensive radioactive decay is evidence of their being themselves the products of the disintegration of other, heavier radioactive elements, that no longer occur in nature, and whose series apparently stretch back towards elements of even larger atomic weights.

Everything that can be learned about this is of the greatest interest for understanding the processes of the universe and, in particular, the origin and evolution of stars and stellar systems.

Plutonium, as we have said, is the basis of present-day atomic power production, and is produced in large quantities. Curium-242 can serve as a concentrated energy source for compact but at the same time powerful atomic batteries, since it combines a long half-life (162.5 days) with high-energy alpha-radiation.

But as we write it is difficult to say what will be future use of the other elements, but investigation of them will undoubtedly open up new and alluring fields.



Chapter Eight

NUCLEAR REACTORS

What is a Reactor?

The nuclear reactor in its improved form, is a wonderful source, capable of supplying man continuously with the power hidden in the nuclei of uranium and plutonium. As a matter of fact, it proved comparatively simple to construct, and the control of its operation is quite reliable.

Nuclear reactors are the basis of modern nuclear engineering. From the preceding chapters we are now familiar with the processes developing in atomic piles. We cannot, of course, describe here all the existing types of reactors or those under development, and it is hardly necessary to do so. Therefore, we shall only acquaint ourselves with a few basic types.

Nuclear reactors can be classified by a whole series of characteristics, according to the moderator employed. Reactors in which the fissionable materials, uranium and plutonium, are arranged in small portions, isolated from each other by a moderator, are referred to as *heterogeneous.*

There are also reactors of *homogeneous* type. In them the uranium is mixed with the moderator, for instance, a very fine powder of uranium or of one of its salts is dissolved in either ordinary or heavy water. (Other liquid moderators are also occasionally used for this purpose.)

There are reactors that have no moderator at all. They work on fast neutrons from the fission of pure uranium-235, plutonium-239 or uranium-233.

Reactors can also be classified according to the energy of the neutrons employed in them. Then we speak of *fast*, *intermediate* or *slow neutron* reactors.

Reactors can further be classified as regards their purpose: e.g. breeder reactors for producing plutonium; research

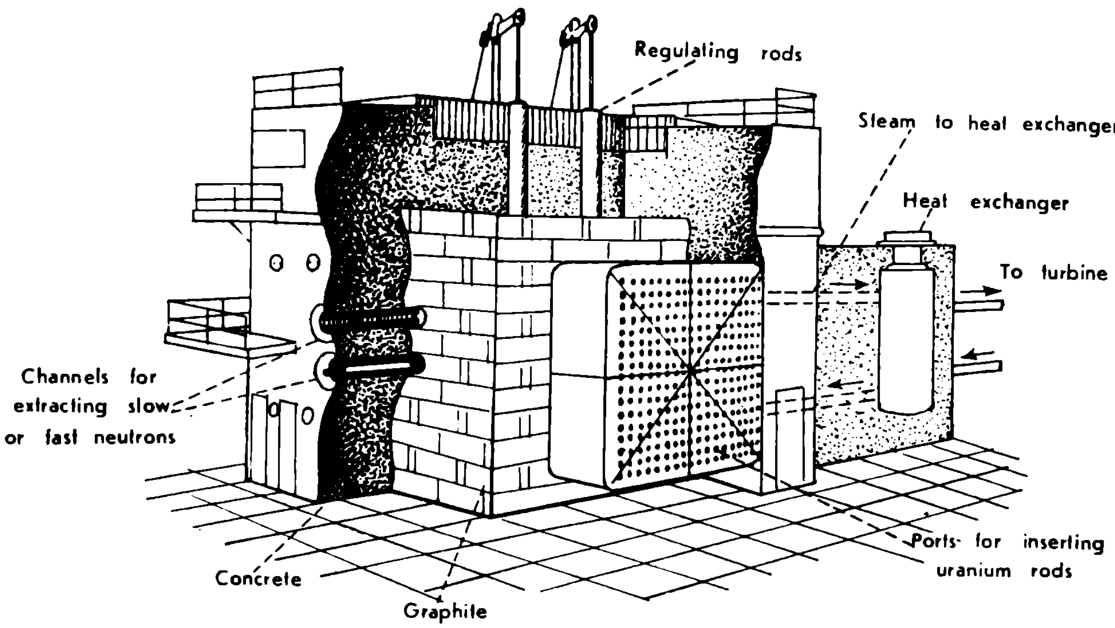


Diagram of the arrangement of a heterogenous reactor, cut away to show the side where fuel elements are inserted

reactors that do not produce plutonium; power reactors employed to liberate heat either for the generation of electricity or for use in engines, and lastly, mixed-purpose reactors suitable for any or all of these applications.

In recent years reactors have come to be classified usually according to the moderator and coolant employed in them, e.g. water-water, graphite-water, etc.

In Pencils and in Reactors

As far as age goes reactors moderated with graphite are the oldest, the first one being built in 1942 under the supervision of Enrico Fermi (see the preceding chapter). Most of the reactors built since then have used graphite as the moderator.

Outwardly a modern heterogeneous reactor resembles the multideck conning-tower of a warship—the same thick grey walls, host of openings closed by massive doors or covered with intricate locks, catwalks, surrounding the superstructure at various levels, and great quantity of apparatus and instruments of all kinds resembling mysterious ordnance. Cranes, winches, and lifts deepen the impression produced by the external structure.

The skeleton of a reactor is a huge frame made up of a great number of long aluminium tubes arranged in horizontal or vertical rows, resembling the honeycomb of gigantic beehives. The tubes are open at one or both ends and into them are inserted, one after the other, many small pellets or rods of natural uranium sealed in metal containers.

After the uranium-235 has undergone fission for a certain period of time, the spent fuel elements are withdrawn. While the reactor is in operation, the tubes are closed with thick, multilayer plugs that block dangerous radioactive radiation.

The uranium fuel elements are arranged only in the central part of the reactor, in its working zone or core, at a distance of three metres or so from

its walls. The cubic lattice of a reactor constructed in this way can hold a score or more tons of natural uranium.

The whole free intertubular space of the reactor core is filled with bricks of graphite of the highest purity that can be produced by the chemical industry. Even one part in a million of an admixture of other substances (most of which usually absorb neutrons) will reduce the effective flux of neutrons penetrating the core of the reactor several times over.

An ordinary graphite-moderated uranium reactor contains several hundred tons of such graphite.

Before a reactor is started up, several strips, coated with a neutron-absorbing substance, are inserted into channels specially provided in the reactor core, and no power on earth can start atomic pile up while these strips are fully inserted into it, for they are designed to prevent it.

A fission reaction only begins as the strips are withdrawn gradually one after another from the reactor. The number of neutrons absorbed by the strips falls gradually until, at last, the moment comes when a slowly increasing nuclear reaction begins to develop in the reactor. By gradually withdrawing the strips a little more after the chain reaction has set in, the average number of neutrons involved in the reaction can be increased until the power of the reactor rises to the maximum (as we explained in our previous chapter).

The rate of a chain reaction is usually regulated by means of one or two cadmium strips. Another two or three strips can be instantaneously inserted into the core of the reactor at the press of a button, should the rate of the reaction exceed the limits of safety. In the event the supply of current to the reactor's control system being interrupted, the strips are automatically inserted into the reactor, or they fall into it, shutting the reactor down.

And that, as a matter of fact, is how a reactor, or the chain reaction developing in it, is controlled.

After the space between the tubes of a reactor have been filled with graphite bricks the core is surrounded with a thick shell of graphite, which serves as a neutron reflector. This reflecting layer makes it possible to reduce the quantity of uranium loaded into the reactor considerably, because of the more effective utilization of the neutrons it provides.

As soon as the reactor is started up radioactive fission products of uranium-235 begin to appear in it in ever increasing quantities, and these products, remaining in the active core of the reactor, are able to absorb neutrons, reducing, thereby, their total flux.

This absorption of neutrons by fission products increases in time to such an extent that normal operation of the reactor is hampered, and there is nothing for it but to replace the uranium rods even although they still contain a certain amount of unsplit uranium-235.

Several blind (closed at the ends) or through channels are usually provided in the reactor core, in some of which measuring instruments are placed: ionization counters, permitting control and automatic adjustment of the chain reaction; counters measuring the density of the neutron flux (number of neutrons passing through one square centimetre per second); thermometers for measuring the temperature in its different zones and units. Other channels accommodate cartridges filled with the various substances that are to be irradiated with a powerful flux of neutrons in order to produce artificial radioactive elements or to study the effect of radioactive radiation on materials.

In a number of designs materials to be irradiated are introduced and with-

drawn by means of special powerful pneumatic devices. A cartridge containing the substance to be irradiated is shot into the reactor by means of a compressed gas (a poor absorber of helium neutrons), and after a certain lapse of time the cartridge is ejected from the reactor directly into a measuring device.

For research purpose it is of great importance to have available fluxes of neutrons of a definite density or certain energy. Reactors are therefore fitted with special devices, thermal columns, enabling a beam of neutrons, covering a range of energies, to be drawn from the core to the outside.

A number of investigations are carried out with retarded neutrons. To make it possible to extract such neutrons from the centre of a reactor, an opening with a cross-section up to 1.5 m^2 is made in the core and the end of a graphite thermal column inserted into it. Neutrons penetrating the graphite column are slowed down in it just as in an ordinary graphite moderator. The thermal column is not intersected by uranium rods or protective layers. Retarded neutrons are extracted along this column into appropriate apparatus on the outside.

The outlet opening in the thermal column is closed with a massive multilayer plug made of lead, cadmium, and steel. Holes of any diameter required can be opened and closed in the plug.

All the devices and instruments of a reactor are usually installed in special laboratories located in adjacent premises (sometimes on the roof of the reactor). The ends of the thermal column and of the ducts and channels that run through the reactor in various directions also finish in these laboratories.

A graphite-moderated uranium reactor may be cooled in various ways.

Low-power reactors and certain experimental ones release comparatively small quantities of heat, which is first absorbed by the mass of the reactor and then lost to the surroundings. They do not require special cooling or heat-removal systems.

Reactors of higher power are cooled by air or gas blown through numerous holes and channels in the graphite bricks of the moderator and in the reflecting shell. Reactors are often cooled by water or some other liquid forced through similar holes in the reactor. The air or water become radioactive.

A most important element of a reactor is what is called the biological shielding against radioactive radiation.

In addition, protection must be provided against the most perfidious microparticles, the neutrons themselves, since they interact very actively with various elements, inducing radioactivity in them.

To ensure complete safety for the personnel servicing a reactor, it is surrounded with a wall made of concrete and substances absorbing harmful radiation. This wall is not less than 2.0-2.5 metres thick and is built not only around the reactor, but also around almost all of its auxiliary devices and associated apparatus. This heavy shielding considerably increases the volume and weight of a reactor. For each cubic metre of effective reactor volume there are 40 to 100 tons of concrete or other shielding.

A Heavy-Water Reactor

Carbon nuclei are six times as heavy as deuterons (heavy hydrogen nuclei), and therefore slow down neutrons only about one-sixth as well. That means, apart from several purely physical advantages, that deuterium, when used as a neutron moderator, makes it possible to considerably reduce the volume, and consequently the weight, of a reactor.

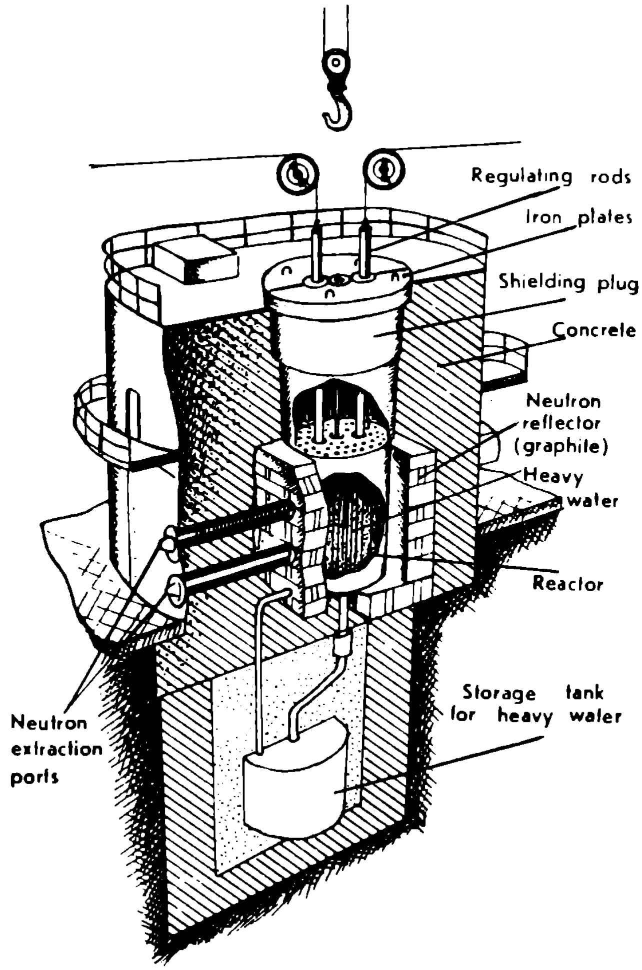
And in addition, the heavy water can be used simultaneously as a coolant.

Here is how such a reactor is constructed.

The basis of the reactor is an aluminium tank about two metres in diameter and 2.5 metres high, with thick, solid walls and holding around 6.5 tons of heavy water. The upper flange of the tank bears upon a well about 60 cm thick built of graphite blocks and serving as a neutron reflector. The well in turn is encased in a metal jacket 10 cm thick, made of two layers of cadmium and lead, the purpose of which is quite cunning; neutrons that penetrate the graphite reflector in spite of its thickness are absorbed by the cadmium layer of the jacket. As the cadmium nuclei become radioactive through absorbing neutrons, they disintegrate and emit gamma-rays, which are attenuated by the lead layer.

The top of the tank is closed by a massive metal cover in which are mounted 120 vertical aluminium tubes, 185 cm long and 2.5 cm in diameter. Special rods carrying aluminium-clad pellets of uranium weighing 2.5 kg each are inserted into these tubes. This arrangement, resembling a gigantic brush, holds up to 2.5 tons of natural uranium. Several other tubes are secured to the cover to accommodate measuring instruments and substances to be irradiated by the intensive flux of neutrons; and other tubes house cadmium rods that are used to control the chain reaction. Like other nuclear reactors, a heavy-water reactor is surrounded by a concrete wall 2.5 metres thick. To facilitate access to it, the top section, which is lowered into the concrete well, is covered with a removable cushion made of layers of lead, cadmium, and steel, several metres thick.

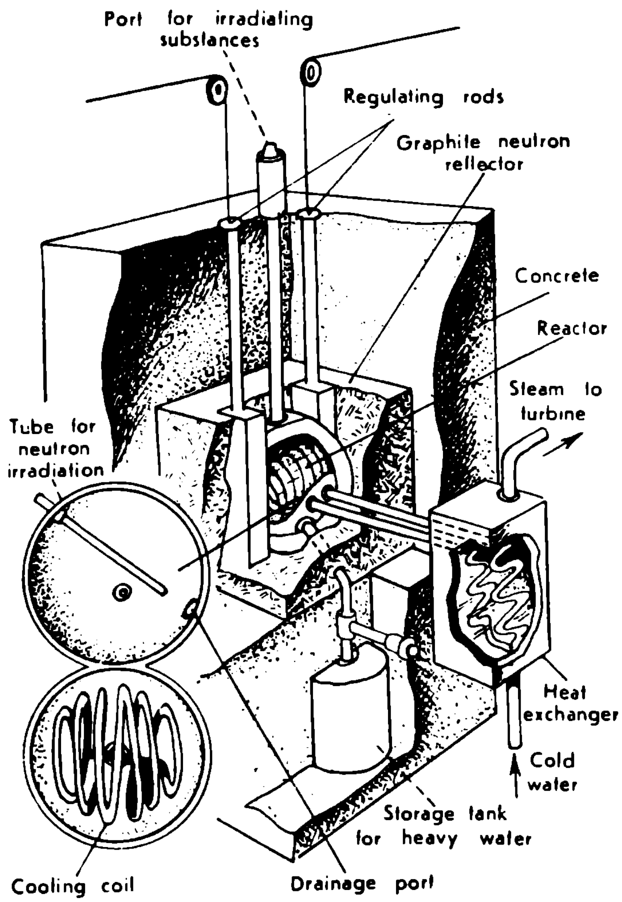
The reactor is cooled with the heavy water, which is also used as a moderator. The coolant circulates continuously



Section of a heavy-water-modulated reactor

between the tank and cooler, which in turn is cooled with ordinary river water or is ventilated intensively by a stream of cooled air.

In addition to the cadmium rods, the reactor can be shut down in case of emergency by means of a special drain valve, which enables the working tank to be emptied in a few minutes, the heavy water being drained off into a special storage tank. Deprived of the moderator, the chain reaction in the natural uranium ceases immediately, since uranium-238 begins to absorb the fast neutrons, and the multiplication factor falls below unity.



A homogeneous reactor with the side cut away to reveal the core, a spherical vessel made of stainless steel and filled with a solution of uranium salt in heavy water

In other respects a heavy-water reactor is similar to a graphite-moderated uranium reactor.

A Homogeneous Reactor

This type of reactor owes its name to the fact that, in contrast to the types considered above, the uranium fuel is distributed uniformly in the moderator and not in individual portions (fuel elements).

For this purpose a uranium salt, like uranyl sulphate, is dissolved in heavy water. Reactors of this type commonly use enriched uranium as fuel, in which the content of the fissile isotope uranium-235 is increased artificially.

The core of a homogeneous reactor is a stainless steel sphere 30 cm in diameter, containing the solution of uranium salt in heavy water.

Owing to the high concentration of uranium-235, the exceptionally small size of the reactor, and the employment of heavy water as a moderator, a chain reaction can be initiated in it with as little as one kilogram of uranium-235 in the solution.

In this respect a homogeneous reactor is rather like an atomic bomb, but it is self-regulating and is practically explosion-proof. Self-regulation is obtained in the following way. When the rate of the chain reaction in the uranium, and hence the power developed by the reactor increases, the temperature of the solution rises considerably. As a result, its volume, and that means the distances between the nuclei of the hydrogen component of the heavy water, increases. The number of collisions between neutrons and hydrogen nuclei, of course, then falls. In these conditions it will take much longer for the velocity of neutrons to be slowed down to thermal speeds. The rate of the reaction diminishes in consequence, and the power of

the reactor drops, the temperature of the solution falls, the hydrogen atoms move closer together again, and the rate of reaction rises to the ordained level.

In spite of the capacity of a solution of uranyl sulphate for self-regulation of the rate of the chain reaction, the reactor is fitted all the same with a set of cadmium rods for fine control of the reaction, enabling its rate to be reduced, and the reactor to be shut down whenever required or in an emergency.

The steel sphere is encased in a lightweight reflecting shield made of two layers of graphite and beryllium. Inside this vessel is a coil in which ordinary water is circulated, cooling the uranyl solution, and carrying heat away to where it will be used.

A homogeneous reactor is the smallest known type of reactor and its power can be raised to a very high level, restricted only by the ability of the coil to remove heat.

But, alas, just like all other reactors, it must be surrounded with concrete shielding not less than 2.0-2.5 metres thick.

Into the very centre of the steel sphere, another tube is introduced, through which powerful beam of neutrons can be drawn from the 'hottest' spot of the reactor to various kinds of measuring instruments. .

The field of application of homogeneous reactors is research, the production of radioactive isotopes, and as a compact source of power for engines.

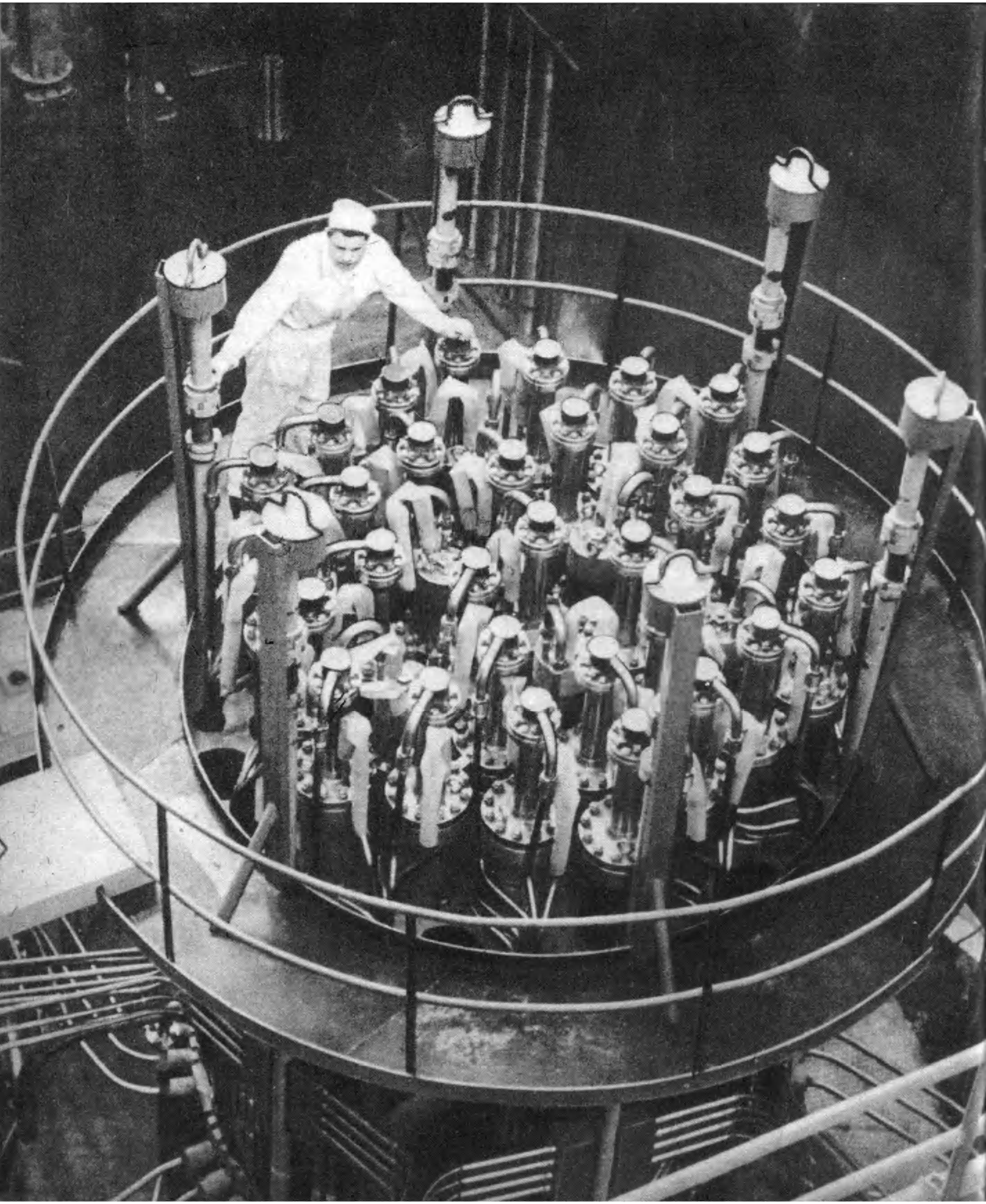
Other vital details about the construction of various types of reactors will be considered in later chapters.

Atomic 'Flames' Under Water

The idea of this reactor arose from the desire to study the ability of ordinary water to absorb the radiation developing in a reactor, and to find out whether it was possible to use it as a neutron moderator instead of heavy water, which was expensive and very scarce. Successful solution of both problems was of extreme importance if reactors were to be used as a source of power for engines of all kinds.

The core of the reactor is an aluminium cage, measuring 40 cm$\times$30 cm$\times$60 cm, holding a great many fuel elements containing plates of enriched uranium. The neutron reflector is a thin layer of beryllium oxide. The reactor is submerged in a pool of around 400 m^3 of ordinary water by means of a light girder and an overhead crane, travelling along rails laid beside the pool.

The overhead crane makes it possible to place the reactor core at any point in the pool, and to lower it to any depth. The neutron moderator is the water filling the pool, which penetrates the space between the flat fuel elements, and serves as well as a coolant. The concrete walls of the pool provide additional biological shielding.



Chapter Nine

A BRAND-NEW INDUSTRY

We are all familiar with and accustomed to the names of such industries as iron and steel, electrical engineering and chemicals.

But the 'atomic industry' now. What does it do? Does it make bombs? Or grade and pack electrons? Or produce and process protons and neutrons?

Strange as it may seem, that is exactly what the atomic industry does, but on an industrial scale, employing all the means of modern science and technology.

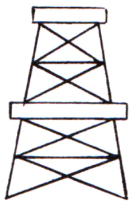
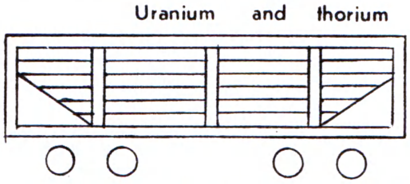
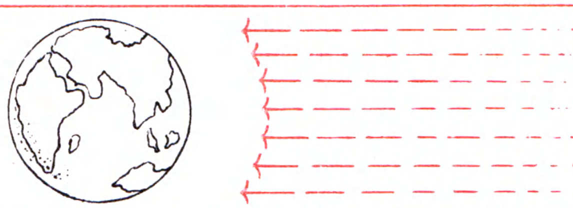
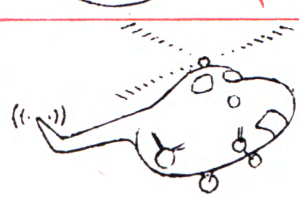
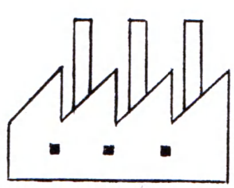
No new branch of science and engineering can influence the industrial and economic might of a country to any extent until it has a well developed industrial base.

In spite of its incomparable merits and advantages, atomic energy would have remained a laboratory 'miracle' for a long time, a 'hurricane in a test-tube', if its development and progress had not been put on a powerful technical and industrial basis not only in the industries directly linked with it, but also in many other older ones (the chemical industries, ferrous and non-ferrous metal industries, the engineering industries, the electrical and radio industries, etc.).

But let us familiarize ourselves with this young field of technology, which arose some 25 to 30 years ago, an industry that employs a great many highly qualified people of the most varied professions.

Apart from that, almost all the older branches of science and technology are occupied to some degree or another with atomic problems (chemistry, metallurgy, medicine, biology, and so on). In fact it is almost easier to count the fields that have not been enriched by the advances of nuclear physics than to name those where they have already found wide application. In another ten years or so there will not be a blank spot on the chart of the penetration of the economy by atomic technology. It is not

World reserves of various kinds of fuel

Fuel	World reserves	Power equivalent, kWh
 Oil	$0.12 \cdot 10^{12}$ cu m	$0.97 \cdot 10^{15}$
 Natural gas	$0.06 \cdot 10^{12}$ cu m	$0.49 \cdot 10^{15}$
 Coal	$10.7 \cdot 10^{12}$ t	$86 \cdot 10^{15}$
Uranium and thorium 	$65 \cdot 10^{12}$ t	$527 \cdot 10^{15}$
	Solar energy reaching Earth per annum	$1500 \cdot 10^{15}$
 	Annual world consumption of power	$3 \cdot 10^{12}$

World energy reserves of various fuels

without reason that our century has been called the 'atomic age'.

Fertile Materials

Unlike gold and platinum, metallic uranium and thorium are not found in the pure state in nature, but only in the form of compounds of various sorts.

The Earth's crust contains as much uranium as lead (0.0005 per cent), but it is extremely dispersed and only occurs exceptionally in rich ore deposits. These ores also contain a whole number of the products of uranium decay accumulated over millions and thousands of millions of years, like radium, polonium, and lead. The main ores or minerals containing uranium are pitchblende, torbernite, autinite, carnotite, and several others.

Uranium is found in almost all countries, but up to the present it has mainly been mined in the Congo, Canada, Australia, and Czechoslovakia, although uranium ores are also extracted in Spain, Portugal, and other countries.

An immense amount of uranium is dissolved in the waters of the oceans (around 3.344 micrograms per litre or a total of $4 \cdot 10^9$ tons).

The crust of the Earth also contains about 0.0008 per cent of thorium, i.e. nearly 1.5 times as much as uranium. The main sources of thorium are what are known as monazite sands, which contain the mineral monazite. Monazite is basically a phosphate compound of rare earth elements and thorium silicate. It is particularly abundant in India, Brazil, and Ceylon.

It used to be supposed that the reserves of energy in uranium and other fertile elements were only a very modest fraction of all the other sources of power. But that has proved not to be so. All the other reserves of energy on Earth are only a twentieth of the power stored in the deposits of uranium and thorium that man will sooner or later be able to extract from the ground and utilize.

At present the world's annual consumption of power is around three million kilowatt-hours (3×10^{12} kWh). At that rate (provided it does not alter much in the future), the reserves of coal and oil on Earth will be exhausted in one or two hundred years; but if we take into account the way power consumption is rising continuously, a shortage of combustible fuels will be felt long before that.

On the other hand, the reserves of energy in atomic fuels—in uranium and thorium alone—can last for thousands of years, even assuming an efficiency of only 25 per cent in the installations transforming it into electricity.

How Uranium and Thorium are Refined

The raw material coming to the refineries that recover uranium metal from ore arrives in the form of rock containing at best one or two per cent of the element. It is therefore considered economically worthwhile to process ore containing even fractions of a per cent of uranium. Of course, the whole mass of ore must first be enriched or concentrated in special mills where as much of the waste as possible is separated from the minerals containing uranium. In this way the uranium content of the concentrated ore may be raised to 20 or 30 per cent, or higher.

Several techniques exist for obtaining uranium metal from the concentrates, but all of them are very labour-consuming and complicated. Let us look at one of the simplest and most common ways employed, as an example.

At the refinery the uranium concentrate is leached with hot nitric acid; the uranium and other metals in the ore dissolve in the acid and dead or barren

World Sources of Energy

Source	In 10^9 tons of standard fuel	In 10^{12} kilowatt-hour
Non-renewable sources (fuels)		
Coal	10 660	86 250
Oil	120	970
Natural gas	60	490
Peat	560	4 550
Vegetable fuel	600	4 800
Uranium and thorium	65 000	526 500
Continuously renewed and practically everlasting sources		
Solar radiation	—	1 500 000
Ocean tides and waves	—	70 000
Wind	—	17 360
Terrestrial heat	—	289
Water power	—	33

rock remains as waste. Then sulphuric acid is added to the solution obtained and as a result insoluble lead sulphate, barium sulphate, radium sulphate, and so on, are precipitated, while the uranium remains in the solution in the form of uranyl nitrate. The mixture of acids containing dissolved uranium is then pumped to special apparatus where enough caustic soda is added to give an excess of soda. This precipitates metals like aluminium, iron, zinc, chromium, etc., which form insoluble compounds (carbonates, hydroxides, and so on). The uranium still remains in the solution, but now as a complex carbonate.

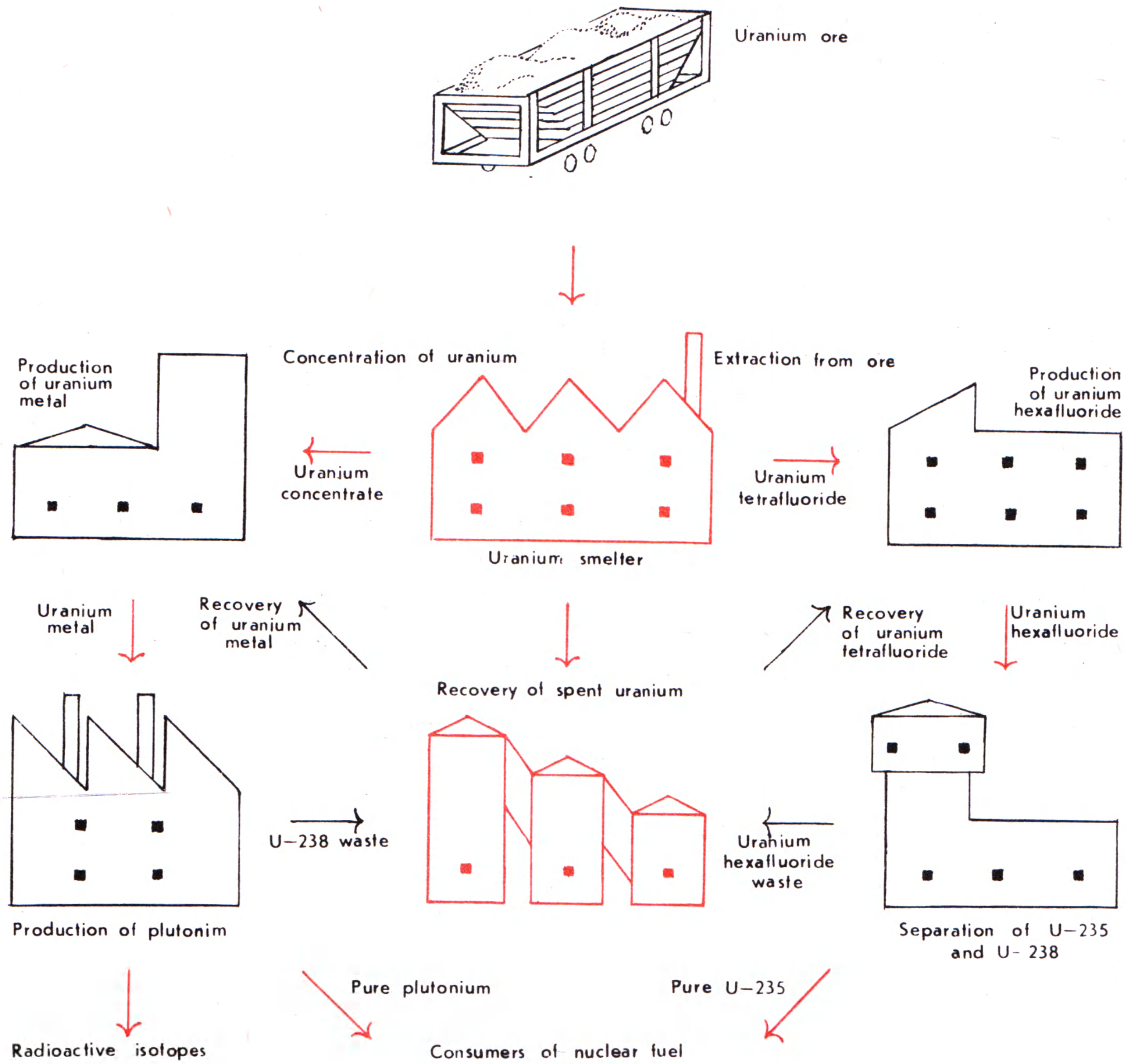
Then the solution is passed into chemical reactors where nitric acid is added until an acid reaction sets in. As a result the complex uranium carbonate is turned back into a solution of uranyl nitrate. Now, when enough diethyl ether is added, this uranyl nitrate all passes into it from the solution, while all the other admixtures remain in the acid solution, or rather, in its aqueous phase.

Since the two solutions, acid and ether, have different densities, they can be easily separated by allowing them to settle. The lighter ether containing the dissolved uranium rises, while the heavier fraction containing the impurities sinks to the bottom and is drawn off from the vessel in which this stage of the process has taken place.

As a result pure uranyl nitrate remains in the vessel, and is precipitated as a bright yellow solid, ammonium diuranate, which used to be mainly employed for painting china and porcelain (before fission was discovered). The ether used to dissolve the uranyl nitrate is extremely inflammable, so the nitrate is washed out of it at this stage with water and then precipitated by means of hydrogen peroxide as uranium peroxide.

The uranium peroxide is first roasted or calcined and then reduced by the action of hydrogen to uranium dioxide.

After that the metallurgical stage of the production process begins. The uranium dioxide is first treated with hydrogen fluoride to turn it into solid uranium tetrafluoride, which is then heated in a steel crucible with chips of calcium. A violent reaction occurs in which the



uranium tetrafluoride is converted into metallic uranium.

The lump or biscuit of uranium obtained is remelted and cast as small cylinders or slugs weighing 2.5 kilograms and which are then clad with aluminium or some other metal to prevent oxidation.

The production of uranium metal differs from most other chemical and metallurgical processes in requiring a product of exceptionally high purity. Even

Schematic diagram of the industrial production of nuclear fuel (uranium and plutonium)

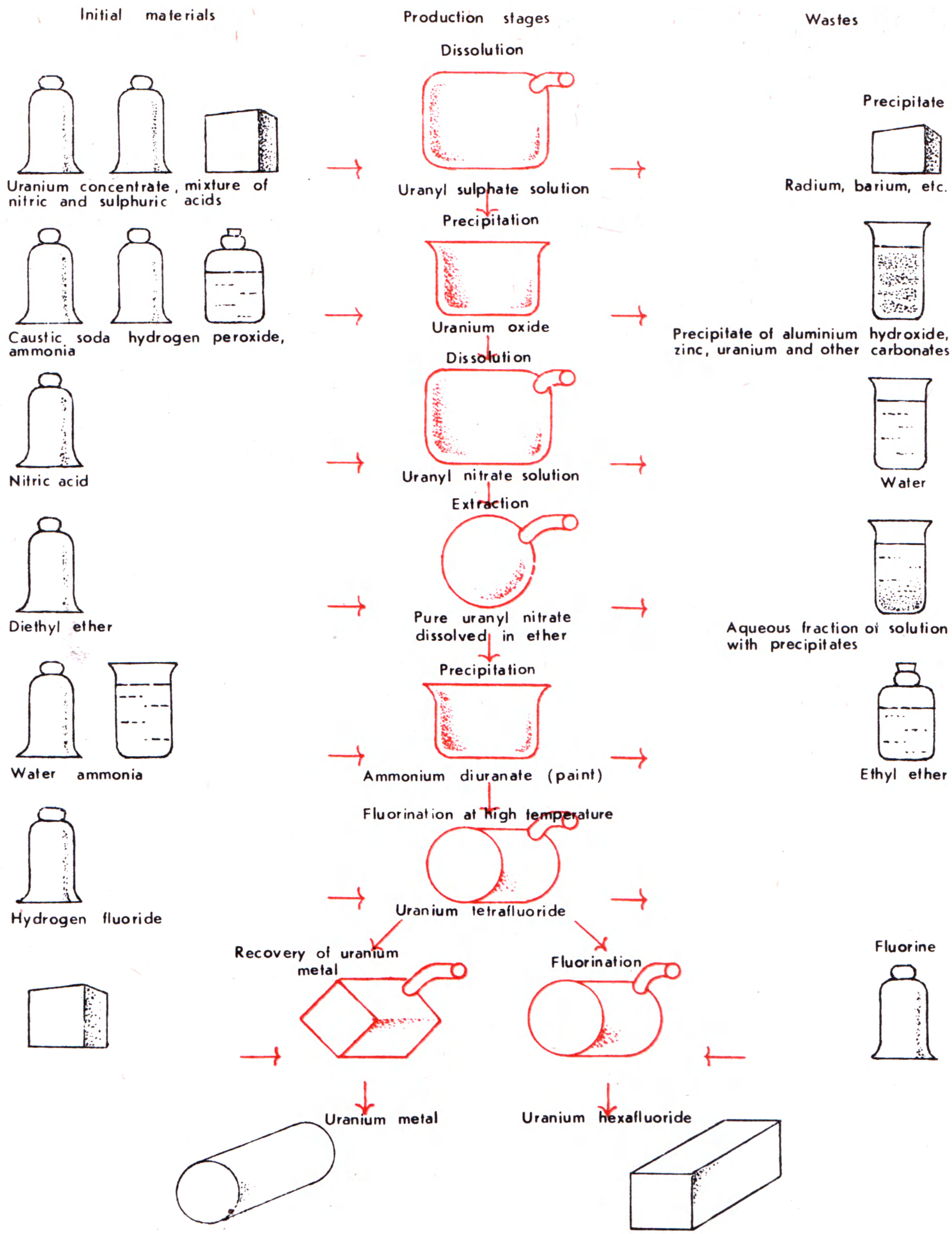


Diagram of a process for producing uranium metal from the raw materials

a minute quantity of some other element is enough to ruin this very valuable nuclear fuel. That is why the extremely good neutron absorbers like cadmium, boron, indium, and many other elements are removed with such very special care. The amount of these elements in a ton of uranium should not exceed one gram.

The dust formed during the production of uranium is extremely harmful to the human organism because it contains very poisonous uranium and lead. The safety precautions must therefore be very strict. The whole production process is so arranged that no dust is formed during the intermediate stages. The shops and departments of the mills have a very complicated ventilation system with instruments to monitor the level of radioactivity in the air. All personnel must wear protective clothing and masks.

The treatment of thorium ore and the production process for obtaining thorium metal are much the same as with uranium. Concentrated monazite ore is first treated with strong sulphuric acid, and then all impurities are removed from the solution obtained by means of phosphoric and oxalic acids. Thorium metal is finally produced by a reduction process.

Factories for Nuclear Fuel

Metallic uranium and thorium are still not nuclear fuel.

To turn uranium metal, for example, into nuclear fuel it is necessary either to separate out the 0.7 per cent of uranium-235, or to burn it out in a nuclear reactor, at the same time converting a certain amount of uranium-238 into plutonium. Which method is used depends on a number of technological considerations.

But how are the isotopes of uranium separated?

There is not a single substance in nature in which one of them can be dissolved leaving the other untouched. Nor is any chemical reaction known that will involve only one of the isotopes and leave the other unaffected.

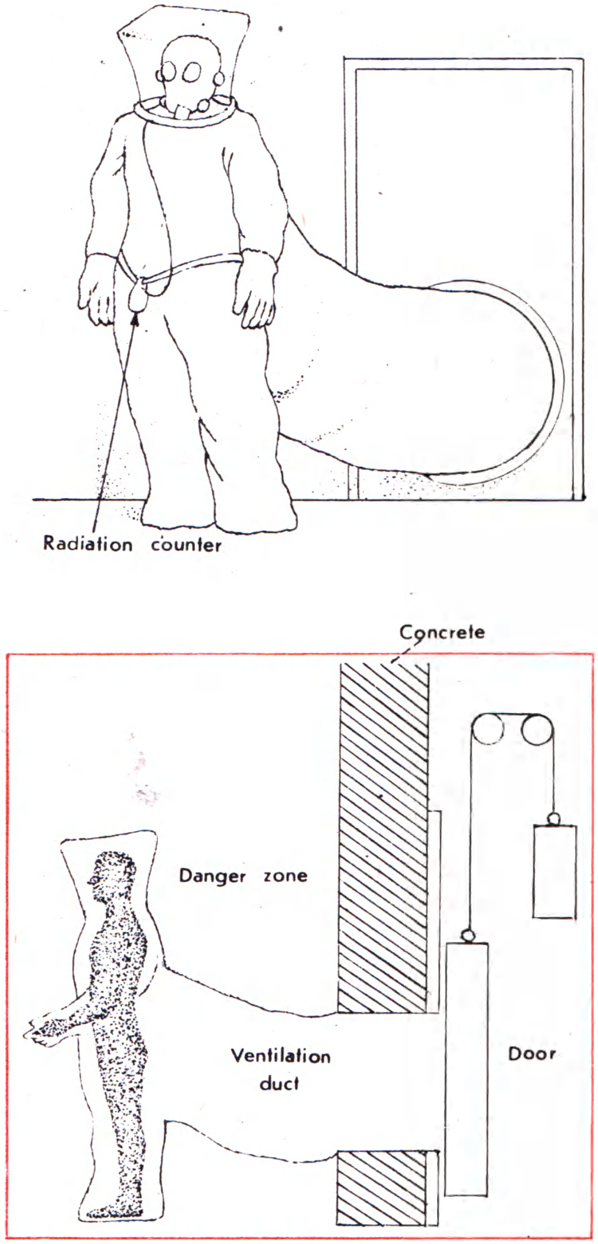
All that differentiates the two isotopes is the mass of three neutrons, which is slightly more than 1 per cent of their total mass. It is only by utilizing this slight difference that they can be separated, and that of course involves tremendous difficulties.

We have seen that the first microscopic quantities of uranium-235 were produced in a device similar to a measuring instrument, the mass spectrograph. Later, in the USA, works were even built equipped with thousands of these delicate laboratory instruments. At the end of a working day only thousandths of a gram of uranium-235 could be scraped off each of their targets; but taken all together they came to a daily production for the whole works of a score or so of grams.

A more productive method was found in gas diffusion. We know from physics that on the average the molecules of a mixture of gases have similar kinetic energies; but that does not mean that they all move at the same velocity. The lighter ones move faster and the heavier ones more slowly.

The light molecules, moving at the higher speed, will hit the walls of the vessel containing the mixture more often than heavy ones and exert a slightly different pressure on it, lower for the heavy ones and higher for the light ones. Now, if one of the walls of the vessel is made of a material containing a multitude of very fine pores, more light molecules will pass out of the vessel in a given interval of time than heavy ones.

The process, however (which is very slow by the way) can only be employed



Workers in the atomic industry sometimes have to do 'armour' like this to protect them

in practice if the lighter gas passes through the porous barrier in one direction only, and cannot get back into the vessel. The gas collected outside the vessel will differ from that inside it in one respect—it will be lighter.

This technique of selective passing of lighter gas molecules through a porous barrier is known as gas diffusion. To use it to separate uranium isotopes the uranium must first be turned into a gas, which means turning it into uranium hexafluoride as that is the only gaseous compound of uranium known. The general layout of a separation plant employing gas diffusion of uranium hexafluoride is shown in our illustration.

In this apparatus each stage or cell consists of two chambers separated by a filter made of a special fine-pore plastic or ceramic material containing a vast number of very fine holes. Gas enriched with U-235 is removed from the outer chamber by means of a powerful vacuum pump. Since one stage of the process gives an infinitesimal separation of the isotopes, the gas must be treated in several thousand cells.

The process of gas diffusion is very sensitive to changes of temperature and pressure, so exact control of the working of the apparatus is very important. When the gas is extracted by pumps and compressors it becomes heated and its temperature rises. Therefore after each stage it must be passed through a special cooler (or heat exchanger) to bring it back to the required temperature.

The plant of a gas diffusion facility is enormous. In addition to thousands of individual cells, compressors, heat exchangers, and instruments and apparatus of all kinds, there are hundreds and thousands of kilometres of tubing, cables, and wiring.

Uranium hexafluoride is extremely poisonous, and its handling calls for special

precautions and protection. In addition, it is one of the most active gases known and reacts with practically all metals, non-metals, and organic materials, and corrodes everything exposed to it. Therefore all the details and parts of gas diffusion plant exposed to it must be made from special sorts of stainless steel, special alloys, and other corrosion-resistant materials.

There are several other methods of separating uranium isotopes, but they are even more complicated than gas diffusion and have therefore not found wide application.

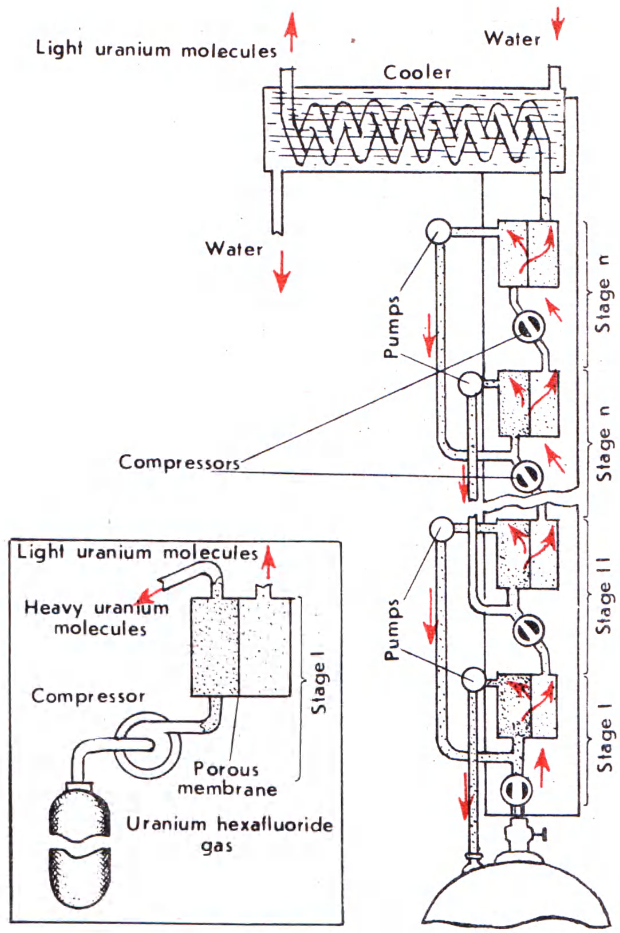


Diagram of the arrangement of the apparatus for separating uranium isotopes by gas diffusion

Nuclear Fuel From Man's 'Second Nature

Here we are concerned with plutonium-239, the element that appeared on earth simultaneously with the birth of the atomic age.

Man's utilization of atomic energy began with uranium-235, and it remains the most important type of nuclear fuel. Even if we had a mountain of natural uranium we could not utilize the tiniest bit of its energy if it did not contain nuclear 'matches' of some sort—even just one atom of uranium-235.

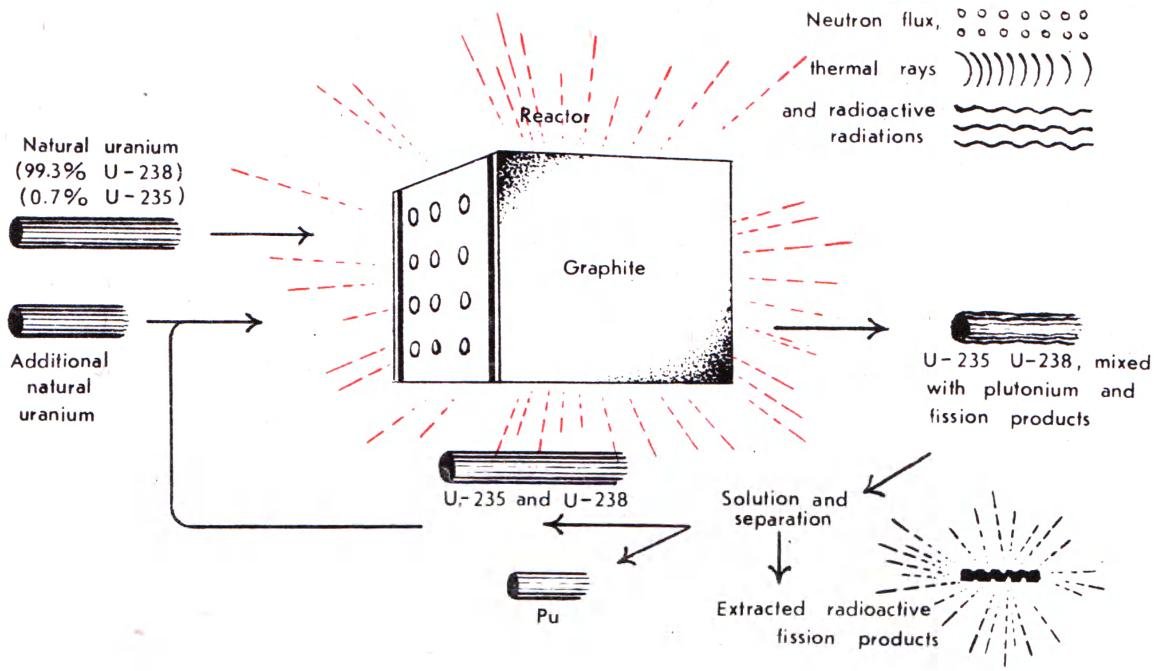
But from the moment the chain reaction of nuclear fission was discovered plutonium also became a very important element. In the near future we shall be able to produce plutonium from all the uranium-238 available, which cannot itself be employed as fissile material; and natural uranium contains 140 times as much uranium-238 as uranium-235.

The main equipment for producing plutonium consists of huge nuclear reactors and facilities for processing the uranium rods removed from the reactors, in order to recover the plutonium in them.

In Chapter Seven we already said something about the technical aspect of the process of converting part of the U-238 into plutonium.

After a certain amount of the U-235 fuel is used up in the course of the chain reaction in the reactor, and plutonium has been formed, the uranium rods are contaminated with a great many radioactive fission products. These 'slags' capture neutrons and slow down or 'poison' the nuclear reaction so much that the rods have to be replaced long before all the U-235 is used up.

The spent rods are highly radioactive and are dangerous to handle even from a long way off. For that reason all the operations involved in removing them



Flow diagram of the production of plutonium from U-238

from the reactor, transporting them, and processing them further, are performed by means of mechanical and remote-controlled devices of all kinds.

The spent rods removed from a reactor are put on special trolleys and submerged at the bottom of a large pool of water (four or five metres deep) built near the reactor for the purpose, and are stored there until all the very short-lived (and consequently very radioactive) isotopes formed by the fission of uranium have decayed.

When this period is over the rods are removed, freed from their protective cladding, and then dissolved in nitric acid. The solution obtained is put through several successive and complicated chemical processes to enable the remains of the U-235 to be recovered, together with the U-238, newly formed plutonium, and the fission products of U-235 (radioactive isotopes of the most varied kinds).

The most valuable and most commonly used radioactive isotopes are first carefully extracted and purified, and the character and energy of their radiation measured exactly; then they are packed in special containers and sent to the numerous customers who use them as powerful sources of various types of radiation—alpha-particles, beta-particles, gamma-rays, etc.

Prior to the discovery of nuclear reactions only a few kilograms of radium were available for the whole world, and the most famous research and medical institutions each had no more than one or two grams of this precious metal. Now one nuclear reactor, even a very powerful one, is insufficient to supply the demand for radioactive isotopes of all kinds with various types of radiation, which are equivalent in radioactivity to many kilograms of radium.

The works that produce nuclear fuel are subject to the same economic laws as other industrial enterprises. As soon as the period of mastering this new branch of technology was over—the pe-

riod of lavish expenditure and drive to obtain the first samples at any price — the iron laws of economics began to take effect. They require production to be carried out with a continuous increase in the productivity of labour, reduction of production costs, economy of raw materials and other expenditure, and lowering of unproductive overheads, and a number of technical measures to improve production, primarily firm steps to raise the efficiency of installations. Lower production targets, and subsidies, discounts, and rebates because of the newness of the business and of real or imaginary contingencies in the technology, and the lack of experience of the personnel are suppressed or eliminated. And when the period of mastering production and of growing pains is over, the most privileged enterprises, while remaining important, special, and priority, for all that become ordinary serial producers.

In the production of nuclear fuel, the main index of the quality of work, technical know-how, scientific level, and skill of the personnel involved is the day-by-day struggle for average of 10 to 1 per cent of neutrons that for one reason or another fail to become involved in the chain reaction processes in U-235 or in the U-238 transmuted into plutonium, or in the thorium-232 converted into U-233.

It is on that, as we saw earlier, that the decision of the basic question—the to be or not to be of nuclear power generation—in general depends; and whether nuclear power will play the main role or just a supporting, though important, part. The last word, as in everything, rests with economics and the development of the productive forces of society. In the capitalist world the decision may take one form, and in the socialist world another.

Atomic energy means not only an era of much energy but also an era of plentiful fertile materials.

The neutron balance in an ordinary reactor in which the 0.7 per cent of U-235 is 'burned up' and plutonium is formed from U-238, at best permits us to obtain half a kilogram of plutonium for one kilogram of fissionable U-235. If the main purpose of such an installation is to produce and accumulate plutonium for atomic bombs, then the work of the enterprise is finished when that is done.

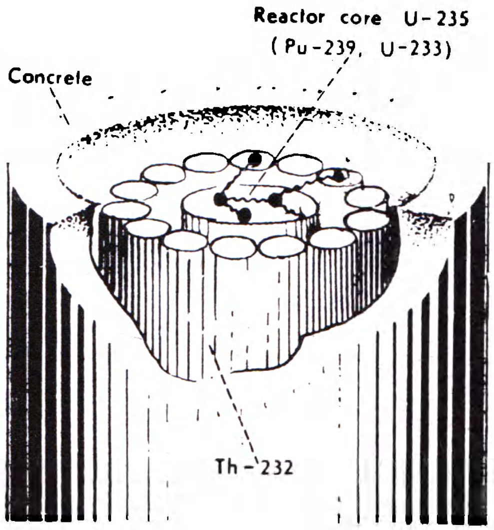
But if its main purpose is to generate electricity, the economics of the whole enterprise cannot rest there. The half kilogram of plutonium produced, mixed again with U-238, creates through decay, let us say, another quarter of a kilogram of plutonium, and that, when mixed again with U-238, produces an eighth of a kilogram of plutonium, and so on. In the final analysis, when the newly created, although constantly diminishing, quantities of plutonium have been fully utilized, not one kilogram of pure nuclear fuel is 'burned' in the reactor, but nearly two, thus almost doubling the amount of energy that can be obtained from the reactor.

Thorium-232

The other element that can be successfully used as a fertile material for artificially produced nuclear fuel, thorium-232 ($_{90}Th^{232}$), is even more common than uranium.

A chain reaction cannot be induced in pure thorium-232 since it undergoes fission only when exposed to very fast neutrons. But when it is irradiated by a powerful flux of neutrons in a nuclear reactor, it is converted into a new artificial isotope of uranium, U-233, which, like U-235 and plutonium, is fissionable.

But production of U-233 is hampered



A scheme for the production of uranium-233 from thorium-232 employing a nuclear reactor of any kind

by the fact that only the one isotope of thorium, thorium-232, occurs in nature, and there is no isotope that can be split as U-235 can be in the uranium family.

To turn thorium-232 into the fissionable isotope U-233, a certain amount of U-235 or plutonium must be added to it, the mixture put into a reactor, and the fuel part of the mixture 'burnt'. Then, as U-233 accumulates, it can be used as nuclear fuel instead of U-235 or plutonium.

We have already said that some neutrons continuously escape from an ordinary working uranium reactor during the nuclear reaction. It can, therefore, prove useful to surround the core with a layer of thorium. After a certain time, when the Th-232 has absorbed enough neutrons some of its nuclei will be converted into nuclei of U-233.

And with that we may perhaps end our description of the industrial production of fissile nuclear fuel, although we have only touched on a comparatively small part of this very interesting 20th century industry.

'Stellar Fuel'

Since we are talking about the raw materials for the atomic industry, we must remember that these also include the materials for the synthesis or fusion of light elements as well as fissile materials like uranium and thorium. The fusion materials are heavy hydrogen (or deuterium), superheavy hydrogen (or tritium), and the light element lithium.

Let us recall the heat-producing capacity of the two kinds of atomic fuel. The burning of one kilogram of the best coal releases around 8.14 kilowatt-hours of energy; one kilogram of uranium or thorium releases about three million times as much energy during nuclear fission, i.e. 22.9 million kilowatt-hours; but one kilogram of hydrogen, when being combined into helium, releases around eight times as much energy as uranium, i.e. 177.5 million kilowatt-hours.

In Chapter Six it was said that the thermonuclear reaction can be brought about in several ways, for example by fusing a tritium nucleus with a hydrogen nucleus (or proton), thus turning it into a helium nucleus, with the release of 19.8 MeV of energy.

When a tritium nucleus fuses with a nucleus of heavy hydrogen (deuterium), it forms a helium nucleus with emission of the excess neutron. This reaction releases 17.6 MeV of energy.

When a nucleus of lithium ($_3Li^6$) fuses with a deuteron, two helium nuclei are formed, releasing an energy amounting to 22.4 MeV, and so on.

When the fusion reaction is induced in pure deuterium two parallel processes may develop at the same time: one, the transformation of two nuclei of deuterium into a nucleus of the helium isotope, $_2He^3$, with the emission of a neutron and release of energy equal to 3.2 MeV; and two, the transformation of two nuc-

lei of deuterium into a nucleus of tritium ($_1H^3$), with the emission of a proton and the release of 4.0 MeV of energy. The newly formed nucleus of tritium ($_1H^3$) fuses at once with a deuterium nucleus ($_1H^2$) to form a nucleus of helium ($_2He^4$), with the emission of a neutron and release of around 17.6 MeV. The reactions may be written as follows:

$$D + D \rightarrow {}_2He^3 + {}_0n^1 + 3.2 \text{ MeV};$$
$$D + D \rightarrow {}_1H^3 + {}_1H^1 + 4.0 \text{ MeV; and}$$
$${}_1H^3 + {}_1H^2 \rightarrow {}_2He^4 + {}_0n^1 + 17.6 \text{ MeV}.$$

Thus, five nuclei of deuterium are involved simultaneously in a complex two-stage thermonuclear reaction with a total release of $3.2+4.0+17.6=24.8$ MeV of energy.

As will be seen from this rather incomplete list of possible thermonuclear reactions, the initial raw materials for the production of thermonuclear fuel are ordinary hydrogen, heavy hydrogen (deuterium), superheavy hydrogen (tritium), and two isotopes of lithium, Li-6 and Li-7. A more convenient, though expensive, source of nuclear fuel is heavy water, with which we are already familiar, and from which heavy hydrogen or deuterium can be separated.

There is an inexhaustible amount of hydrogen on Earth, and also plenty of heavy water, when you think how much water there is in the oceans (for every six tons of ordinary water contain one kilogram of heavy water).

The total quantity of water on our planet is around 1.4 million million million tons (1.4×10^{18}) and scientists have calculated that it contains at least 25 million million tons of deuterium (25×10^{12}).

The fusion of one gram of deuterium into nuclei of helium yields 100 000 kilowatt-hours of energy, so the amount of energy in all the deuterium on Earth is roughly equivalent to 3×10^{20} kilowatt-years compared with an annual world energy consumption of around 3×10^{12} kilowatt-hours.

The only practical method of obtaining heavy water is electrolysis, i.e. repeated dissociation of ordinary water by electric current, each successive dissociation yielding a residue of water gradually enriched with heavy water. But this process requires enormous quantities of electricity, about 60 000 kilowatts to produce one kilogram of heavy water, in which the two atoms of heavy hydrogen are still united with one atom of oxygen. An additional process is needed to separate the deuterium from the oxygen.

The superheavy isotope of hydrogen, tritium, is an even more convenient raw material for thermonuclear fuel; but it occurs in very small quantities in nature, being formed probably by the interaction of powerful cosmic particles and elements in the atmosphere.

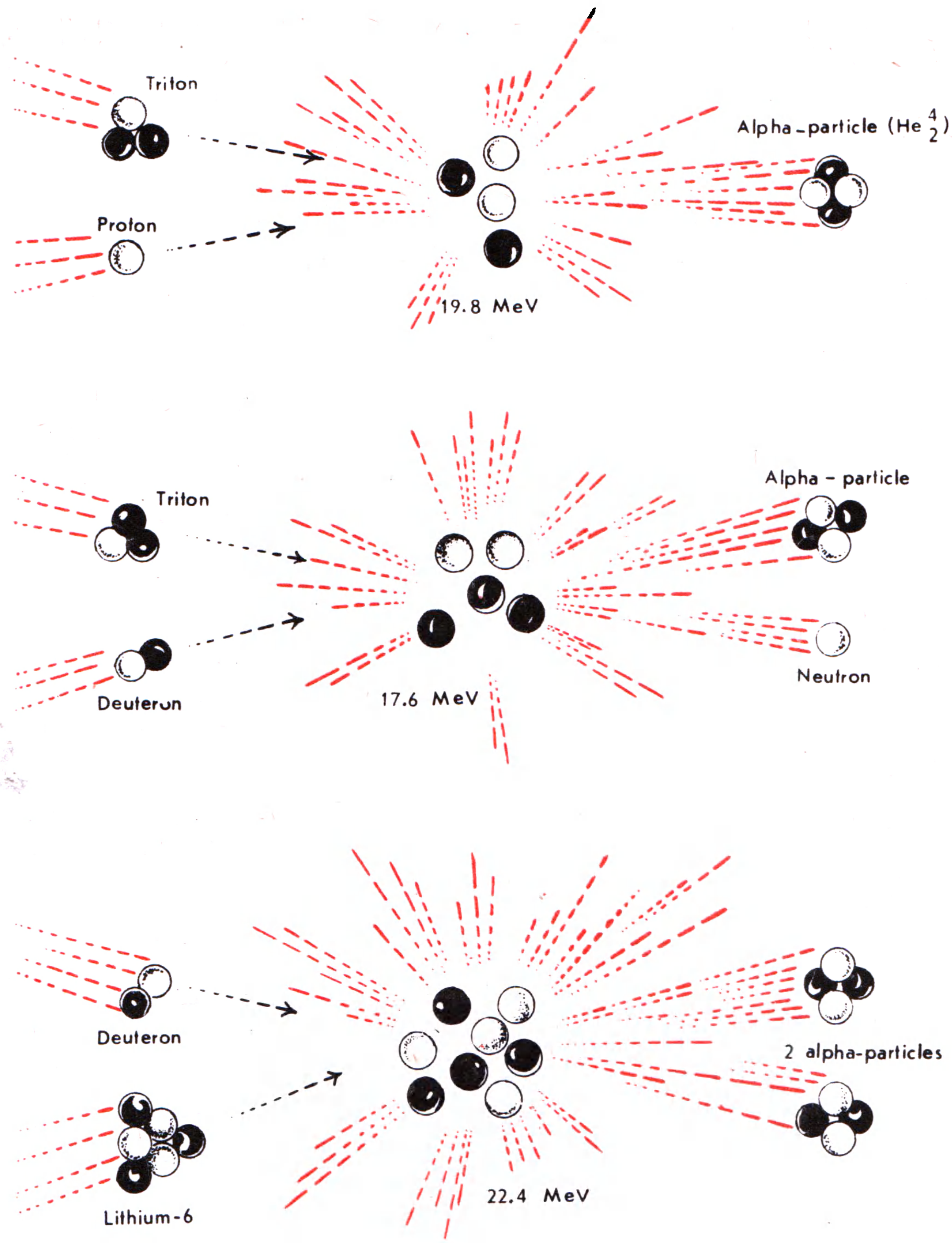
Therefore tritium can only be obtained artificially, by exposing the isotope lithium-6 to neutron radiation in a nuclear reactor. Lithium is quite abundant in nature and is a constituent of more than 150 minerals.

The Li-6 irradiated in a reactor dissolves in water, and when the solution obtained has been electrolysed, it is possible to separate out hydrogen containing a minute admixture of tritium.

Another method of producing tritium is to blow hydrogen into molten, irradiated lithium. The tritium formed as a result of the irradiation will be mixed with hydrogen but can be separated from it comparatively easily.

But apart from being a source of tritium, lithium-6 can unite with deuterium in certain circumstances, and lithium-7 with hydrogen, to yield a thermonuclear reaction.

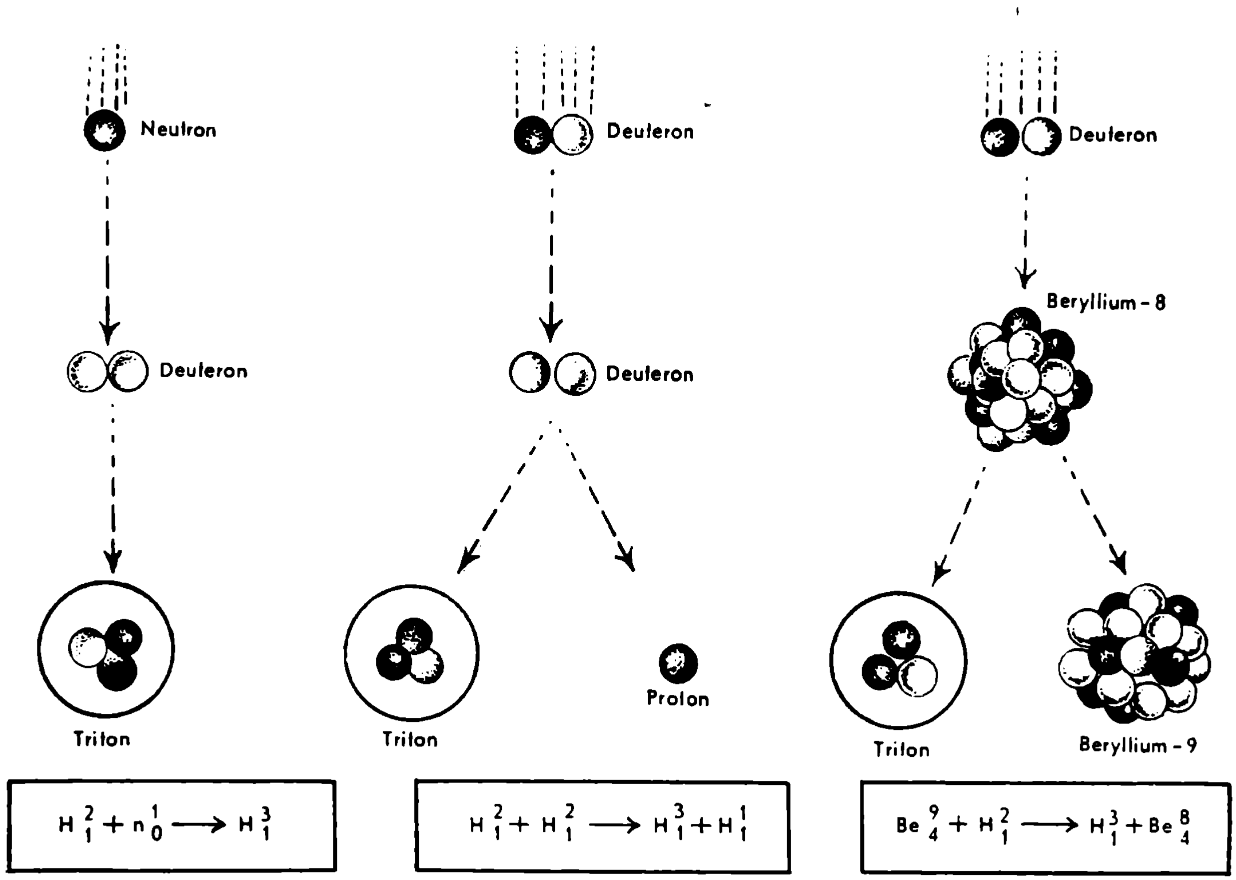
Thermonuclear reactions are the main source of the energy emitted by the Sun



Some of the fusion reactions for combining the nuclei of atoms of light elements into nuclei of heavier elements and the energy released as a result

and stars and for that reason hydrogen and lithium are occasionally called 'stellar fuels'.

The genius of man, however, has resolved the seemingly impossible task of creating a thermonuclear reaction in terrestrial conditions. After the atomic bomb had been made, the problem was

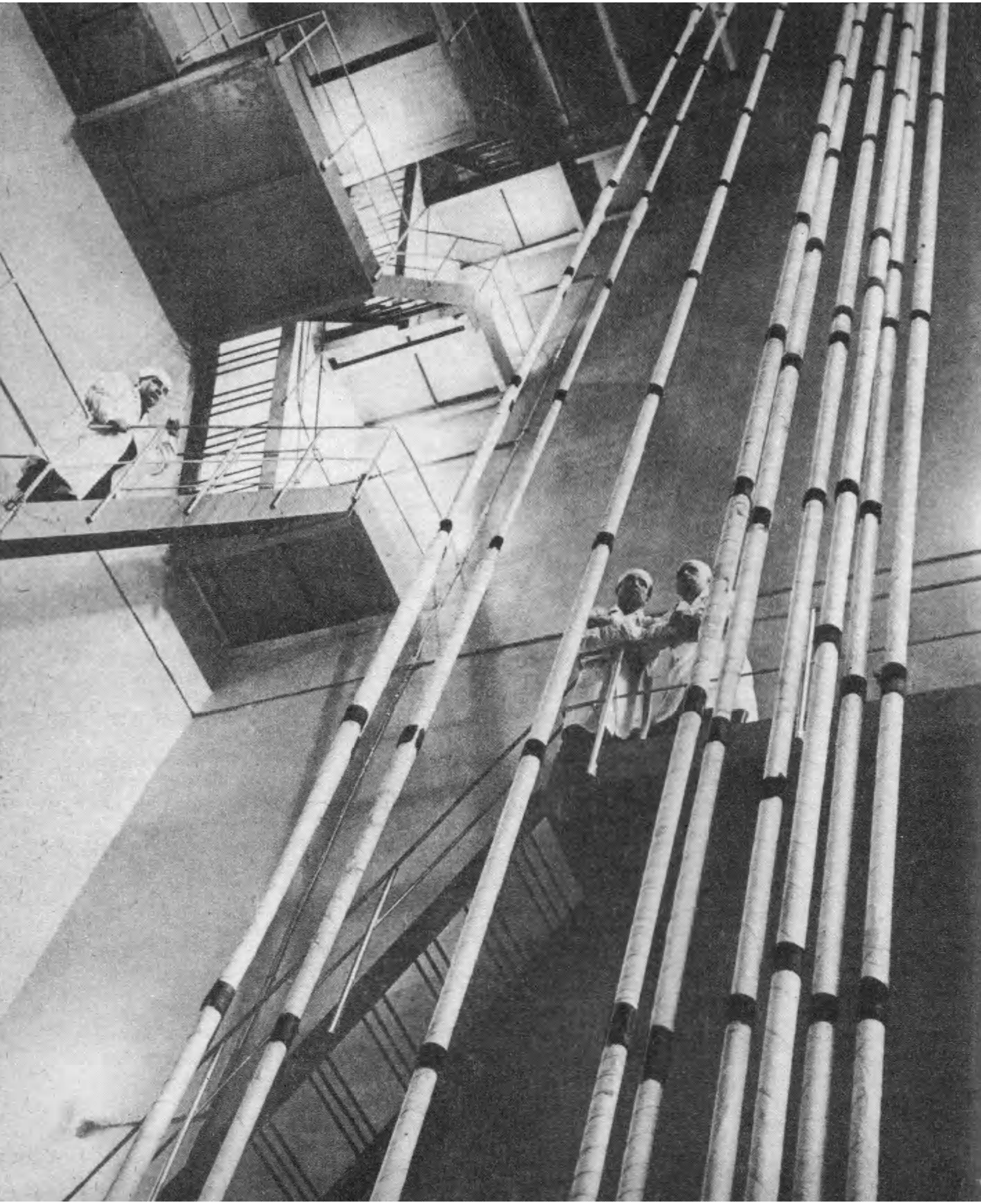


Possible ways of obtaining tritium by bombarding deuterium and beryllium with various particles

solved in an apparently very easy and almost ordinary way. We sometimes even forget that we have entered the age when man, almost on the heels of obtaining an incredibly powerful force, the energy of nuclear fission, laid his hands on an even more powerful force, the energy of thermonuclear reactions with which he can really work miracles if he uses it properly. Alluring prospects have opened before us, and cosmic space is no longer inaccessible. The man of the future may even be able, if he wishes, to create an artificial sun.

Of course, only the first step has so far been taken toward utilization of this powerful force. We can still only use it in the form of a gigantic explosion. But the time is coming when man will learn how to moderate it, and convert it into 'small change', and then he will literally have a real bit of a star in his hands, blazing with a dazzling flame.

Is it possible to curb this new, superpowerful energy? We shall try dreaming about it in Chapter Seventeen.



Chapter Ten

THE MARCH OF ATOMIC POWER

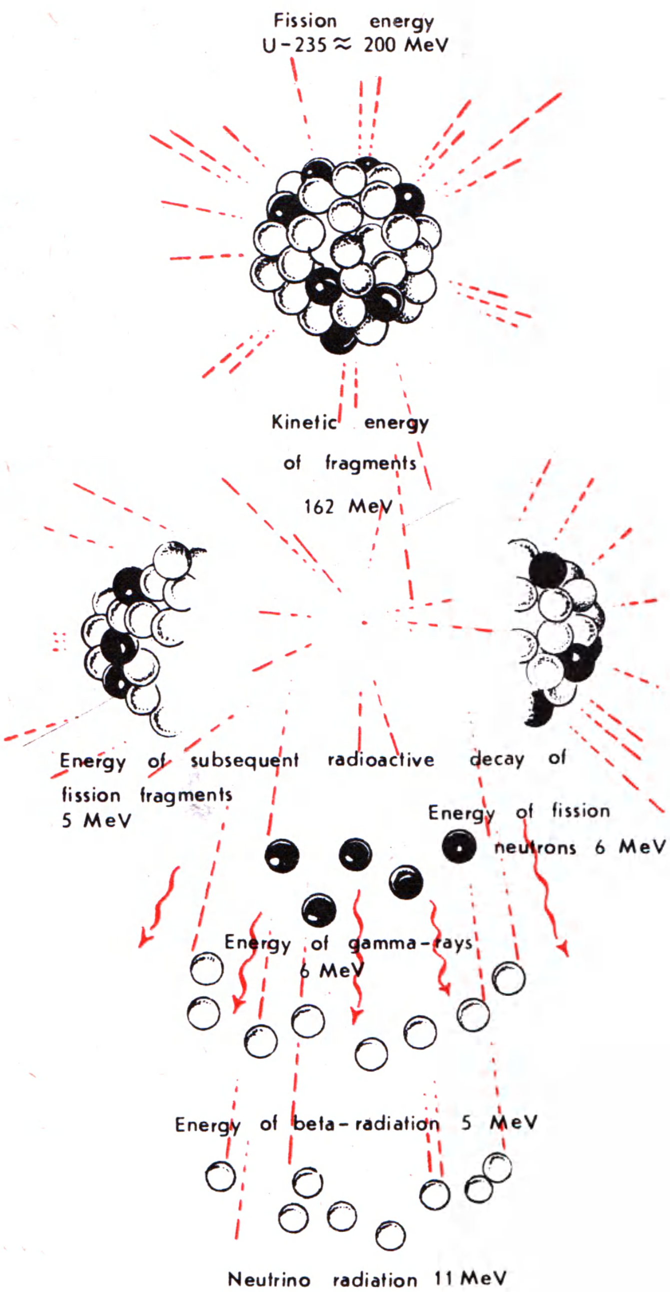
How Much Longer Will People Burn Money?

In spite of the continuous construction of gigantic hydroelectric power stations and the vast resources of water power available the bulk of the coal, peat, oil, shale, and natural gas produced in all countries is still burned in the furnaces of thermal power stations. If we add in the fire-boxes of steam locomotives, and all the various kinds of furnace, stove, and oven, the merciless fire burns up more than 90 per cent of all the fuel extracted in a year.

As long as these materials were thought of solely as fuel scientists and engineers were comparatively unworried. They were mainly concerned to produce as much oil and coal and other fuels as possible and to consume them in the best way possible. The only thing they could not accept was that the most perfect steam locomotive converted only 6 to 8 per cent of the fuel burned in it into useful work, while 92 to 94 per cent of the heat literally went up the flue. And the best thermal power station did the same with 65 to 70 per cent of its fuel.

At the beginning of the 20th century, however, this rather distressing circumstance became aggravated. Chemical science had made such big, important, and far-reaching strides that it became necessary radically to reconsider whether we were employing the bounteous gifts of nature in a sensible and thrifty manner.

The very fuel that we burn so wastefully, whether it is ordinary wood or oil, contains extremely precious raw materials needed in most branches of the economy. The value of the products that can now be made or extracted from combustible materials is hundreds and thousands of times greater than their value as fuel. Coal alone can be used



The energy released by the nuclear fission of uranium-235 and the radiation that carries it away

to produce such valuable things as petrol, alcohol, rubber, lubricants, synthetic fibres, plastics, medicines, and explosives. And the list gets longer with every passing day as newer and newer items are added to it.

The great Russian scientist Mendeleev, giving the facts one day on the value of the products contained in petroleum, said that to use oil as fuel was tantamount to heating a stove with paper money. In the future, therefore, men will undoubtedly use these very important sources of raw materials as such instead of wastefully burning them. And we should bear in mind that the world's output of fuels of all kinds is now at least 5 000 or 6 000 million tons a year!

Steam Boiler vs Nuclear Reactor

The total quantity of energy released by the nuclear disintegration of uranium-235 is approximately 200 MeV. Of this energy, 162 MeV, or about three-quarters, is carried off by the two fragments that fly apart with tremendous velocities. For that reason, it has proved most expedient at this stage of our knowledge in the field of nuclear power engineering to utilize the energy of the reaction primarily as a source of heat.

When a nuclear reactor is intended for peaceful purposes, such as the production of electricity, no scientifically or technically minded person, with atomic energy at his disposal, would agree to waste it in installations less efficient than any now available. On the contrary, the new science and technology call for much more advanced means of converting energy. That means they must be capable of competing with very effective plant, because modern steam turbines operating on superheated steam at temperatures of 600° to 650°C and pressures up to 300 atmospheres have an efficiency of 38 to 41 per cent.

And as a nuclear reactor must enter into competition with such a turbine as a kind of steam boiler, it must have characteristics and parameters not a whit inferior to those expected of modern steam boilers.

But when we try to employ a reactor as a source of heat for steam-generating equipment we run into a whole series of fundamental difficulties.

A steam boiler is specially designed to withstand the tremendous pressures developing in it; but such pressures are inadmissible in a nuclear reactor since it is a complicated and difficult business to adapt it for them.

Unlike a steam boiler, a reactor can develop any power, but only provided the immense amount of heat generated in it is removed immediately. Otherwise local overheating will take place in some component or another, resulting in the melting either of the uranium rods themselves or of their cladding. The reactor would then become contaminated with radioactive fission products and have to be shut down.

The heating surface of a steam boiler exposed to the cooling medium can be increased as much as desired. But the core of a reactor, which becomes heated during operation, is small and it is difficult to increase the surface exposed to the coolant, in some designs even impossible.

What way out can technology suggest? Is it possible to build a reactor as efficient as a modern steam boiler without creating too high a temperature inside it, and especially too high a pressure?

The problem can be solved in one of two ways. One is to build a reactor in which the temperature can rise to 450° or 500°C or higher by employing new heat-resistant materials (zirconium and titanium alloys, etc.) combined with carefully considered design and other improvements. For that purpose, the cooling water must be circulated at a pressure of 100 atmospheres or higher to prevent it from boiling.

The other way, which is no less difficult, is connected with several interesting and attractive circumstances.

Ordinary methods of heat exchange by means of a jet of cooling gas or stream of water are not adequate to remove the vast amount of heat involved. So a number of modern reactors are cooled with liquid metals like mercury, sodium, potassium, etc. Liquid sodium, for example, boils at a temperature of 880°C. That means that heat can be removed from a reactor using liquid sodium (or potassium) at a pressure no higher than that of the atmosphere. At that temperature water would be converted into steam with a pressure around 160 atmospheres.

The heat transfer coefficient of liquid metals is much higher than that of steam. They absorb considerably fewer neutrons. And in addition, because of their high thermal conductivity, very much less liquid metal is needed to cool a reactor than water. Consequently cooling a reactor with liquid metals makes it possible in principle to raise the working temperature inside a reactor considerably and to ensure an efficiency comparable with those of modern boilers.

In practice, however, it is extremely difficult to build a reactor that will stand up to the temperatures suitable for using liquid metal and to avoid the greater local overheating.

And there is yet another serious obstacle. The corrosion of metals and other materials rises sharply with increase of temperature, as we know, and in the presence of radioactivity it is catastrophically accelerated for a number of materials.

There are materials and alloys that

are very resistant to the effect of radioactivity and high temperatures but they also, unfortunately, absorb neutrons readily and so are of little use in reactors.

We could list many more difficulties, large and small, that stand in the way of building atomic power installations. But let us now examine the advantages that would accrue from an atomic power station, compared with an ordinary thermal one.

In the first place it would not be necessary to haul several trains of coal to it every day and to remove at least a quarter of it again as clinker and ash. Instead of the 1 000 to 1 500 tons of coal a day required by a 100-megawatt thermal power station, an atomic power station of the same capacity would consume only 200 to 250 grams of U-235, as much as would fill a tablespoon. The annual supply of fuel for the station could be delivered in a small van or by plane.

It follows therefore that an atomic power station, once built, can be absolutely independent of railways and will need no special tracks or sidings leading to it. It can be built practically anywhere that power is needed.

An atomic station also operates without the powerful draught of air that is needed by thermal stations in order to intensify combustion. So an atomic station does not contaminate the atmosphere with soot and smoke, and does not consume vital oxygen.

Lastly, an atomic power station can be completely automated and be operated without the presence of any staff.

The First One In the World

The date 27 June 1954 is an important one in the history of atomic power. On that day the whole world heard the communique of the Soviet Government that, for the first time in the world, a power station had begun to generate electricity in the USSR working on the energy released by the nuclear fission of uranium.

It seemed almost unbelievable that this terrible power had been harnessed for peaceful purposes.

Let us enter the world's first atomic power station. The modest white, three-storey building looks more like a boarding school for sick children or a hospital than a power station. Only the high chimney suggests that it might be an industrial building.

And although we know it is a power station supplying a still modest 5 000 kilowatts of electricity to surrounding farms, and towns, and factories, there are no signs of sidings, lorries, cranes, or trestles. Not a thing.

Electricity is being generated through the continuous fission of nuclei of U-235. The daily consumption of the station is ... guess! ... 30 grams. A similar station using the best coal would need at least 100 tons a day.

Notice that word we used for its 5 000 kW—'modest'. People are so used to the size of modern generating stations—640 megawatts, 1 000 megawatts, 2 100 megawatts, 3 200 megawatts, 5 000 megawatts—that 5 000 kilowatts (5 megawatts) seems tiny.

In fact engines of that power are now installed on aircraft. Four thousand years ago, to obtain such power, the Pharaohs of Egypt would have had to harness 100 000 slaves. In the middle ages it would have needed 10 000 horses. And during the time when Britannia became mistress of the seas her whole fleet of sailing ships did not develop such power.

One crosses the threshold of the first atomic power station in the world with quite understandable emotion.

The main thing that strikes one is the amount of shielding against radiation.

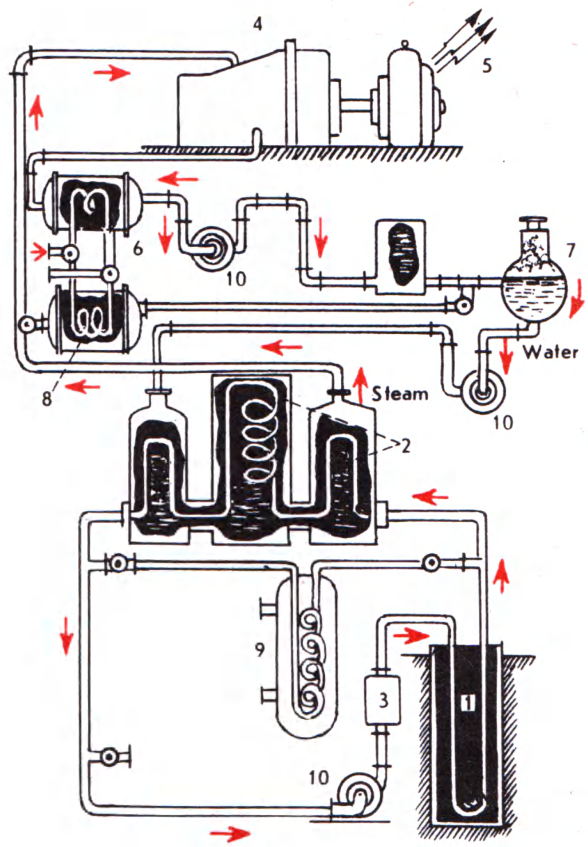
All the working premises are isolated from each other by concrete walls and partitions as thick as the walls of some old fortress. The doors resemble those of the strongest safes. And the corridors near the 'heart' of the station, the reactor, even run in a zig-zag manner like frontline trenches. Wherever invisible and deadly gamma-rays might break through they are blocked by protective concrete barriers.

The reactor is located in a wide hall, or rather under the floor of the hall, into which only its upper, protective cover protrudes. It works with slow (thermal) neutrons, slowed down by a graphite moderator. Its core is a vertical cylinder, 1.5 metres in diameter and 1.7 metres high, composed of closely laid graphite blocks, and encased, in turn, in a thick graphite shell that serves as the neutron reflector.

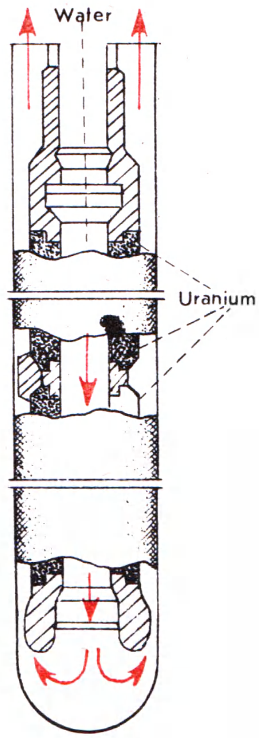
The graphite cylinder of the core has vertical holes at strictly determined distances from each other; into 128 of these holes so-called working rods, long twin tubes with double walls, are inserted from the top by means of a special travelling crane. The gap between the double walls is filled with uranium; and cooling water is circulated through the tubes, as shown in the picture. When inserted into the reactor each working rod is connected with the inflow and outflow water tanks of the cooling system.

Other holes in the graphite cylinder are for the control rods, which can be lowered into them to any depth desired, or withdrawn, in order to control the development of the chain reaction; and still other holes are for emergency rods that are inserted to shut down the reactor in case of emergency.

Alongside the hall is a room in which there are enough spare working rods hanging from the walls to keep the station working for half a year. Because



Working scheme of an atomic power station: *1*, water-cooled nuclear reactor; *2*, heat exchanger; *3*, filter retaining substances, that could become radioactive if they entered the reactor; *4*, steam turbine; *5*, generator; *6*, steam condenser; *7*, deaerator; *8*, starting condenser; *9*, stand-by condenser; *10*, pumps



The main item of the complex 'organism' of the first atomic power station, a water-cooled uranium fuel element

of the low radioactivity of natural or metallic uranium, these rods present no danger to the staff and can be handled without special precautions.

But when a rod of spent fuel is withdrawn from the core special precautions must be taken, since it contains dangerous highly emissive fission fragments Workers only come into the hall to hook the crane to the holder on the top of the rod and leave at once. Then an automatic system is switched on. First the upper, harmless part of the rod is pulled out of the reactor, followed by the lower, 'hot' part, 1.5 metres long, which is emitting an enormous quantity of dangerous gamma-rays, and has a radioactivity equal to that of ten kilograms of pure radium.

That is why the rods are removed from the core by means of remote-controlled devices, and why their withdrawal is observed through a window of thick glass impervious to gamma-rays, set in a thick concrete wall.

The 'hot' rod must be locked up as soon as possible in a safe 'dungeon'; so as soon as it is withdrawn from the reactor it is immediately transferred to special premises and plunged into a deep pool of water where it is kept for a year until the 'hottest' fission products of U-235, which emit strong, penetrating gamma-rays, have decayed. Then, and only then, will the rod be processed so as to extract the plutonium formed in it and the other fission products.

There are several other openings running across the graphite cylinder of the reactor and in them are instruments that measure the density of the flux of neutrons inside the core. These instruments are connected to special devices that regulate the position of the control rods in such a way that when the density of the neutron flux rises the rods are pushed deeper into the reactor and the rate of the chain reaction reduced. Then, when the flux weakens, the rods are withdrawn slightly from the reactor.

The whole reactor, including the graphite neutron reflector, is encased in a cylindrical steel vessel, which, together with the bottom and the top cover (made of thick steel plates), forms another hermetically sealed shell around the power source. Inert gas is pumped into this shell, which prevents oxidation of the components of the reactor through radiation.

As we know, natural uranium contains only 0.7 per cent of the fissile U-235. If the reactor was operated with such a small amount of U-235 it would never be able to develop the energy required, and the fuel rods, moreover, would need to be changed too frequently.

So it is loaded, not with ordinary uranium, but metal enriched with as much as 5 per cent of U-235. This enrichment of the fuel elements increases their life in the reactor to 100 days. This reactor contains a charge of around 550 kilograms of enriched uranium.

The outside of the steel vessel of the reactor is surrounded by a strong biological shield to protect the staff of the power station against radiation. The shield consists of a layer of water one metre thick, mainly to capture any neutrons that have passed through the reflector; concrete walls three metres thick, mainly to absorb gamma-rays; and a layer of cast-iron plates 25 centimetres thick, laid over the top of the reactor in order to absorb any vertical gamma-rays.

But protection for the staff is not restricted to this shielding of concrete walls, water jackets, and steel shells. The power station also has a good safety or radiation monitoring service. All around the reactor and in other working premises is placed a host of ionization chambers connected to the special central panel of the monitoring service. From readings of the instruments on the panel the duty radiation supervisor estimates the degree of radioactive contamination of the air in any room and the quantity of radiation penetrating it. He then gives whatever instructions are called for, increases the ventilation of the premises, and orders the personnel to evacuate the hazardous room until a safe dose of ionization is registered there.

But that does not satisfy the meticulous doctors and engineers of the monitoring (or dosimetric) service. Every person of the staff of the power station has a personal radiation dosimeter, an instrument resembling a fountain-pen or a small powder compact or vanity case. Inside this dosimeter there is a piece of film specially sensitive to gamma-radiation. Every four days the film is developed and compared with precisely checked and calibrated standards. If on a Tuesday, for example, the blackening of his film shows that a worker has already received the admissible but still safe dose of radiation laid down by Soviet doctors after long and careful research, he is not allowed to come near the reactor until the next Tuesday, and the whole team of the radiation monitoring service starts a search for the cracks through which dangerous radiation is penetrating. No such cases have in fact been registered during the history of Soviet atomic power engineering, but the doctors remain extremely vigilant just the same.

The most complicated thing about atomic power stations is the transfer of heat to a steam turbine. How was that done in the first Soviet one?

The water flowing through the reactor and exposed to its powerful neutron flux becomes high radioactive and it is consequently impossible to use its steam to drive a turbine. Therefore the water used to remove heat from the reactor, which does not boil, although it is heated to 270°C, because it is under a pressure of 100 atmospheres, is circulated in a closed system (referred to as the first circuit), which embraces the reactor itself, high-capacity pumps, and a steam generator known as a heat exchanger.

The steam generator is a strong steam boiler within which there is a coil linked to the first circuit. Water from the first circuit is forced through the coil, and in passing heats the water of the boiler (which circulates through what is called the second circuit) to a high temperature. On coming into contact with the very hot coil of the first circuit this water is converted into steam at high pressure, which then actuates a steam turbine driving an electric generator.

The main feature of the heat exchanger is that the radioactive water of the first circuit does not come into direct contact with that of the second circuit, and does not transfer its radioactivity to it. Therefore the steam coming from the heat exchanger is harmless and no kind of protection is needed since it does not give off radiation. But the pumps and pipes of the first circuit must be guarded in the same way as the reactor itself, since the water passing through them to the steam generator, although it has been carefully cleaned to remove impurities (since they become major sources of radioactivity when exposed to neutrons), is radioactive.

Having passed through the coil of the heat exchanger the water of the first circuit has cooled to 190°C and is returned to the reactor. Water heated above 100°C, incidentally, is able to absorb and remove heat better than very cold water.

The water in the second circuit circulates at a pressure of only 12.5 atmospheres, so that it turns into steam at a temperature equivalent to 235°-250°C, which is then passed to the turbine. After driving the turbine, the steam goes to a condenser where it is cooled and turned back into water which is then pumped by a special system of pumps and pipes to the heat exchanger to be evaporated again. Thus the circulation of water here, too, is done in a closed circuit.

The first atomic power station had four steam generators, one of which served as a stand-by heat exchanger.

If the reactor can justifiably be called the 'heart' of an atomic power station, the central control panel is its 'brain'. From this command point all parts of the complex process of converting atomic energy into electricity are controlled by two duty engineers. At every step, special indicators continuously follow or monitor the work of the reactor and other parts of the generating station, and sensitively react to the slightest deviation from the prescribed conditions. Numerous lights and audible signals indicate what has happened and simultaneously tell the cause of any trouble or disturbance in the operation of the reactor and the other parts of the station. Any deviation is corrected immediately by automatic devices, and whatever it is it does not change the power output of the station for a second.

The design of atomic power stations is gradually being simplified. Many fears and doubts disappeared at the very beginning. And many more will vanish as time goes on. This new source of power, superior to any that has ever existed or been used by man down the ages, has already become part of our life.

New Ideas

The 5 000-kW Soviet atomic power station was not simply an industrial undertaking; it was designed primarily to demonstrate the fundamental scientific and technical feasibility and the undoubted desirability of converting atomic energy into electricity. So it was more a constructive laboratory for gathering the experience needed to solve the host of practical, operational, and economic problems involved—whether or not atomic power stations would be profitable compared with existing thermal and hydro-electric power stations.

The experience of the work fully justified the hopes of the scientists. Since the day it was commissioned there has been no breakdown of any importance at the power station and no accident to the staff. The reality and technical feasibility of long continuous generation of electricity by means of the energy of nuclear fission was brilliantly demonstrated.

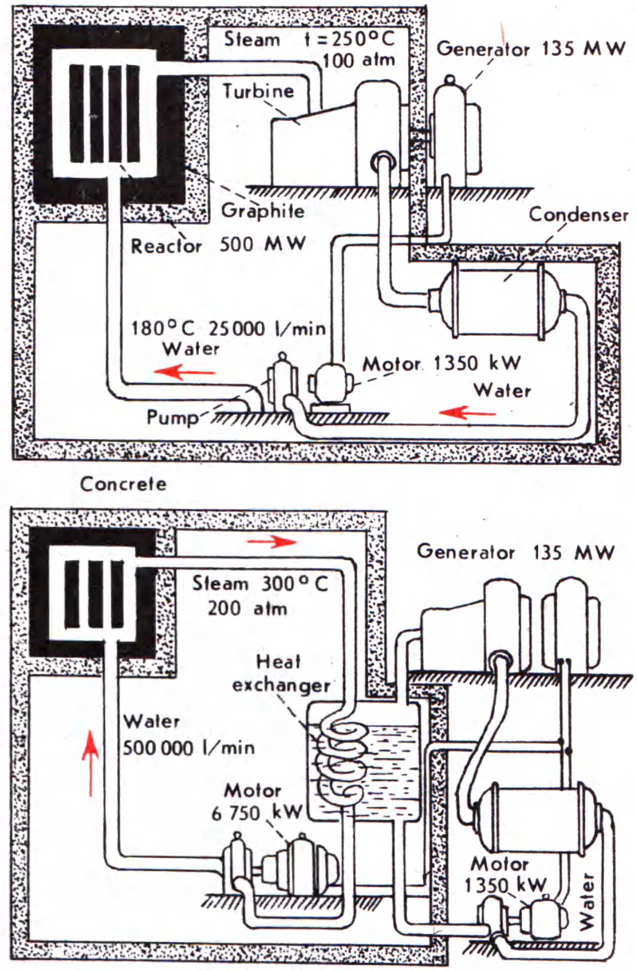
The cost of the electricity generated at this first atomic power station proved to be several times higher than the cost of electric power generated in conventional thermal power stations, as was to be expected. This was mainly due, however, to one reason, its relatively low power. As the capacity of atomic power stations increases the difference in cost gradually diminishes, and at a power rating of 400-600 megawatts there is almost no difference whatever. That means that atomic power stations are subject to the general law that the greater the capacity of a power station the cheaper will be the cost per unit of the electricity generated by it. At even higher capacities atomic power stations should be cheaper than thermal ones.

What kind of technical improvements and innovations can be expected in the design of nuclear reactors and atomic power stations in the foreseeable future? Let us touch briefly on the most interesting and important ideas in this field.

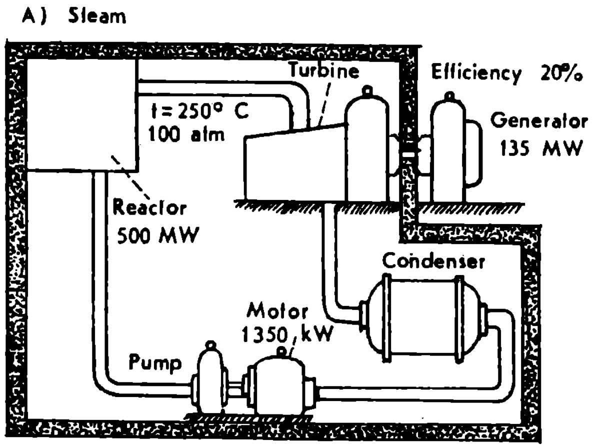
We have already spoken about the drawbacks in a layout that does not include a heat exchanger, namely the presence of boiling water and high-pressure steam in the reactor; the fact that radioactive steam must be passed through the turbine and through all the intervening components; and the fact that it is necessary therefore to erect shielding around all these units as well as around the reactor, so that servicing is hampered. But such a layout also has a number of advantages. A comparison of the two layouts—with and without a heat exchanger—is given in the illustration; the output of each station in it is 135 megawatts at an efficiency of 27 per cent.

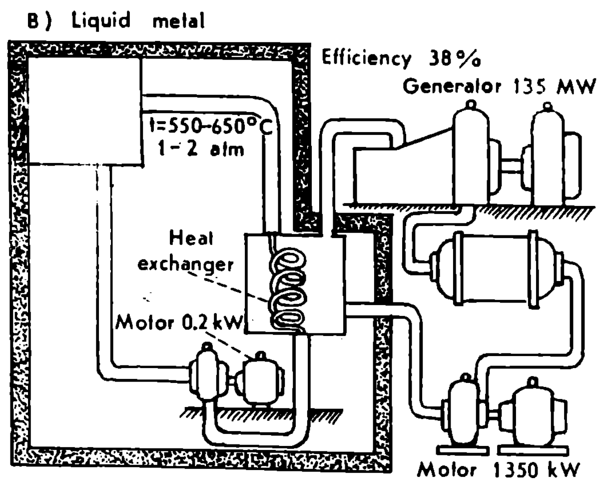
What are the advantages of dispensing with a heat exchanger?

For one thing, the station thus has many fewer individual units. To work at a water temperature of 250°C, its



Performance characteristics of an atomic power station depending on whether or not it incorporates a heat exchanger





The advantages of liquid-metal-cooled reactors over water-cooled ones

reactor must be designed to withstand a pressure of 100 atmospheres, while a reactor with a heat exchanger must have a steam temperature of 300°C to compensate for the loss of heat from the heat exchanger, and a pressure of 200 atmospheres.

The power consumed by the pumps to circulate the cooling water drawn from the turbine condenser through the reactor at a flow rate of 25 litres a minute is around 1 350 kilowatts, or 1 per cent of the terminal capacity of the generator.

In the power station using a heat exchanger, another 6 750 kilowatts or so (5 per cent of its capacity) must be used to circulate the water in the first circuit that removes heat from the reactor, in addition to the 1 350 kilowatts needed for circulation in the second circuit. Therefore a power station without a heat exchanger needs 1 per cent of its output for its own needs, while a station with a heat exchanger needs 6 per cent. That is quite a big difference, big enough not to reject the layout without a heat exchanger in spite of its drawbacks, which after all can be overcome.

The advances of mechanics and telemechanics make it possible to control and regulate contemporary power stations without the presence of people on the spot.

Heat-resistant, high-temperature alloys and materials are available, and new grades are constantly being developed, that are resistant to the corrosive action of the radioactive steam driving the turbine, and flowing through the condenser and main pump.

But here we must say something about what is called induced radioactivity.

Like any other substance water and steam are exposed to an intense flux of neutrons inside a reactor. And by absorbing neutrons, the nuclei of the ele-

ments of which water is composed, and also of any impurities that are in it, become artificial radioactive isotopes that, on disintegrating, emit beta-particles and gamma-rays. For these gamma-rays to give rise to secondary or induced radioactivity in most substances exposed to them, their energy must be at least 8 MeV; but no known natural or artificial radioactive element emits gamma-rays of such energy. Therefore the shielding of the power section of an atomic station need only be designed against the radioactivity of the coolant or heat-transfer medium, and against the radioactivity of remnants of water and steam accumulating or leaking into different sections of the layout, when coolant is withdrawn from the system.

Nevertheless it is necessary to build a defensive concrete shield not only around the reactor but also around the turbine, the pump, and the system of pipes, a drawback that sometimes restricts the use of such power stations.

In modern high-capacity boilers water is more and more often replaced by mercury, liquid sodium or potassium or a mixture of the two, or other liquid metals, for reasons we have already explained; but a great many other technical difficulties arise in planning such reactors. (How liquid sodium compares with water as a reactor coolant is shown in the table below.)

It is difficult, for example, to confine liquid sodium in a circulating system when it has been heated to a very high temperature. The pipes expand and the joints may leak, letting it escape, and the reaction of liquid sodium with damp materials, even in the slightest quantity, is a destructive explosion. An equally grave situation can occur if water gets into liquid sodium. In addition high-temperature liquid sodium rapidly corrodes pipes and metal exposed to it so that quite weak or simply unreliable link can develop in an extensive system of tubing. There are also other, even greater complications that we have no space to go into here.

Reactors that use ordinary water as the moderator, and often as the coolant as well, present great interest, and have a great future. And among the designs of heavy-water reactor, there is one we must mention specially, the homogeneous 'boiling-water' type in which uranium is dissolved in heavy water. It has several advantages that make it very promising, as follows.

In the final stages of the production of uranium metal there is a quite complicated process of reducing it from the oxide, with an equally complicated process of refining it to remove all traces of impurities. With a homogeneous reactor it is not necessary to obtain the metal from uranium oxide since the latter dissolves comparatively readily in heavy water. Thus production costs

Characteristics	Liquid sodium	Water
Operation pressure, atm	5-8	100
Temperature at reactor inlet, °C	300	190
Temperature at reactor outlet, °C	550-650	250
Melting point, °C	104	0
Thermal efficiency, %	30-35	20-25
On reacting with water and damp air	Dangerously explosive	Safe
On reacting with graphite	Does not decompose	Decomposes

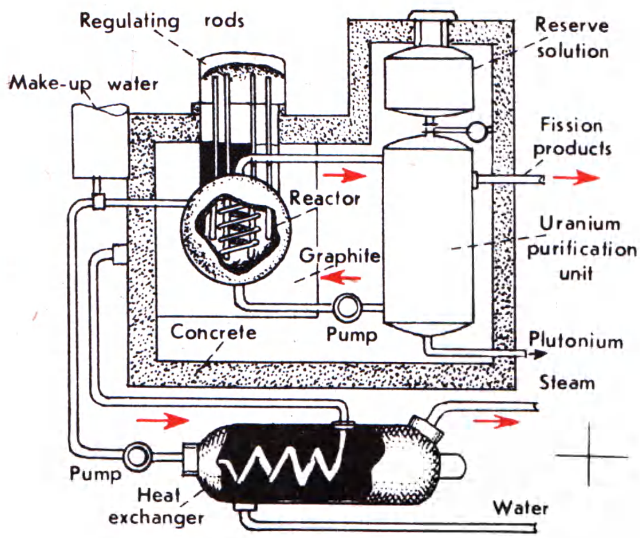


Diagram of a nuclear reactor with continuous removal of fission products

can be cut and the loss of uranium in 'waste' during the refining of the metal reduced.

When the U-235 is burned up in an operating homogeneous reactor all the liquid and gaseous slag—fission products—pass into the heavy water, from which they are more easily recovered than from slags of uranium metal.

Finally, there is another, very important point. A homogeneous reactor can be so designed as to ensure continuous circulation of the uranium solution. While one fraction of the solution is working in the reactor another is simultaneously passing through a purification process during which fresh U-235 is added and plutonium is recovered. That can be extremely important when a reactor must work for a long time at full power, for example, as the engine of a spacecraft.

It has also been suggested that it is possible to create a rather unusual new type of reactor in which the atomic fuel, moderator, and coolant could all be combined, while preserving the advantages offered by liquid for the recovery of fission products. The layout of a reactor embodying this idea is illustrated in the figure.

A uranium salt is dissolved in liquid bismuth which practically does not absorb neutrons at all. This solution is then circulated continuously in a closed circuit through the reactor, the heat exchanger, and the plant where fission products and plutonium are extracted from the mixture, and the burned-up U-235 replaced.

Normally the solution would undergo a nuclear reaction only in the reactor core and nowhere else in the circuit. Any neutrons arising from the spontaneous fission of a comparatively few nuclei of U-235 would freely escape from the mixture since the circuit outside the reactor would not be clad in a moderator and neutron reflector; so the mixture is quite safe as regards the possibility of a spontaneous reaction, and even safer as regards the possibility of an explosion.

When the mixture enters the reactor, this is what happens. The core is surrounded by a neutron reflector that immediately prevents the escape of neutrons from the uranium-bismuth mixture. And the many channels in the core through which the mixture flows at high speed are surrounded by a neutron moderator, either graphite blocks or heavy water. Naturally, in such conditions, the neutrons are instantly slowed down to thermal velocities and begin intensively to split nuclei of uranium-235. The scattered fission products or fragments heat the mixture to between 500° and 800°C. As soon as the mixture leaves the reactor the chain reaction in the uranium in it immediately ceases, so that the mixture acts solely as a heat-carrying medium on its way to the heat exchanger. Then, having given up the heat it brought from the reactor core to the water (or another

liquid metal) in the heat exchanger, the mixture is purified of fission products and returned to the reactor.

The possibility is not excluded, of course, that as better materials are invented we shall be able to return to designs that have seemingly been rejected once and for all, and to old tested coolants like water and gas, instead of searching for new, and very often complex and costly, methods of removing heat from reactors.

When One Log Becomes Two

When we were young we often used to be told the fairy tale about the magic pot that was always full of tasty porridge no matter how much was eaten, or the one about the even more bountiful table cloth that served up the most varied dishes. The reactor that scientists with no inclination for fabulous names have more severely called FR-5 (fast reactor, 5 000 kW) acts in just that fairy-tale manner.

It was developed by a group of Lenin prize-winners, A. I. Leipunsky, member of the Ukrainian Academy of Sciences, Prof. O. D. Kazachkovsky, and engineer M. S. Pinkasik.

What is so fabulous about their reactor?

Well, suppose you were asked whether it was possible to burn 100 kilograms of wood or coal in a boiler, use the heat to do a certain amount of work, and then take all the fuel burned back out of the fire-box plus some extra? You would immediately think your questioner was a crank who had discovered perpetual motion, or a bad writer of amazing stories, or just a plain ignoramus. You would naturally deliver him a lecture on the impossibility of perpetual motion, on the laws of the conservation of energy and mass.

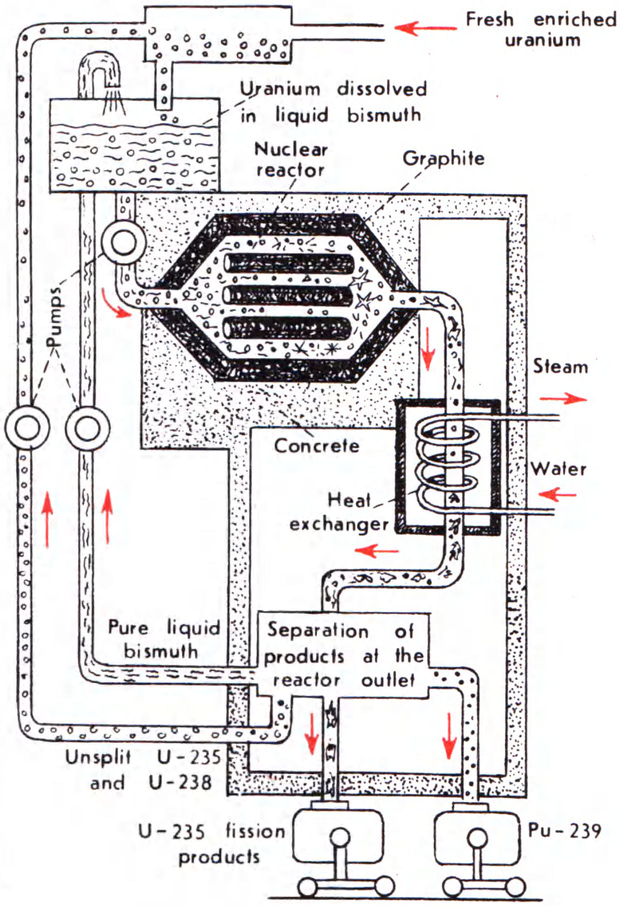


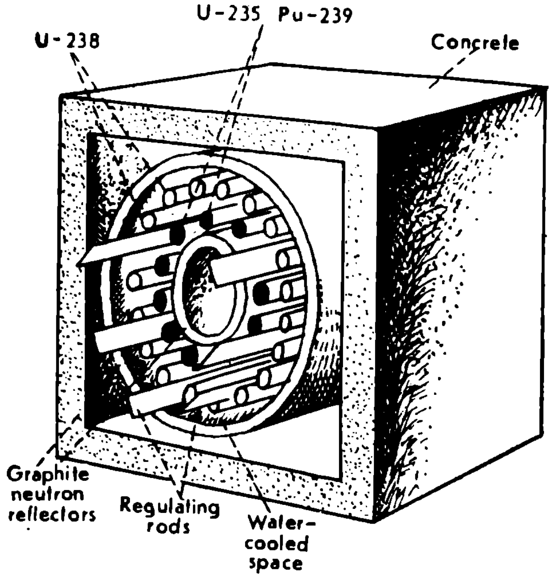
Diagram of a nuclear reactor in which nuclear fuel, moderator and coolant are combined in one fluid

But there is a furnace that gives the fuel back, what is called the breeder reactor.

But how does that happen? Have scientists succeeded at last in discovering perpetual motion, this time atomic?

Of course, no one has succeeded in discovering even atomic perpetual motion, but it is apparently possible to get back from a reactor more fuel than is consumed in it. It is a matter of the kind of nuclear fuel used now, and what can be used in the future.

We have already said several times that natural uranium contains only 0.7



Schematic layout of a breeder reactor. A series of breeder reactors makes it possible to utilize one hundred per cent of natural uranium instead of the 0.7 per cent of U-235 contained in it

per cent of U-235, the only element that can be used for a self-sustaining chain reaction. The other 99.3 per cent of uranium metal consist of U-238 and U-234, which do not take part in the reaction and are, as a matter of fact, ballast. U-235 can either be separated from the U-238 at the outset, and used as fissile material, or, without resorting to preliminary separation, it can be burned out in a reactor When that is done, a very small fraction of the uranium (about 0.3-0.5 per cent) is transmuted into plutonium, which can be separated from the U-238, and so on until the ever diminishing quantity of the newly formed plutonium shrinks to zero.

It is then possible to burn up more than the initial 0.7 per cent of U-235, and accordingly more energy or heat is released. But in reactors of this type no plutonium will be left to be used for other purposes.

The experience gained by scientists from operating reactors suggested a bold idea to them. Would it be possible to construct a reactor in which, during the burning of the 0.7 per cent of U-235, not 0.3-0.5 per cent of the total amount of U-238 would be transmuted into plutonium, but an equal of 0.7 per cent, or perhaps even 1.0 per cent more.

For if it were possible to use all the U-238, turning it into plutonium, the power reserves available to humanity would be increased more than one hundred times.

Appropriate theoretical studies and practical experiments showed that the problem could be solved.

How can such a breeder reactor be built?

Arranged at the very centre of the core is a definite quantity of pure U-235, less than the critical mass, of course. A violent start to the nuclear reaction is prevented by an adequate number of neutron-absorbing cadmium strips, inserted fully into the core before starting-up.

Since the pure U-235 is used as nuclear fuel, there is no need for moderators of any kind, and the chain reaction in the uranium is brought about by fast neutrons.

The arrangement of the nuclear fuel in a compact mass makes it possible to reduce the size of this part of the reactor, and to use a minimum number of structural parts: stands, pipes, girders, etc., that inevitably contain neutron-absorbing elements.

The central rod of U-235 is surrounded by a solid shell or blanket made of U-238. The fast neutrons escaping from the central core penetrate this shell and, on being absorbed by nuclei of U-238, transmute them into plutonium (Pu-239).

The whole reactor is encased in an ordinary neutron-reflecting graphite layer, surrounded in turn with biological shielding metres thick.

The reactor is cooled and heat removed from it, and its operation controlled via holes provided in the central rod of U-235, in the blanket of uranium-238, and in the reflecting layer of graphite.

In such a reactor a chain reaction sets in as the coarse-control cadmium strips are withdrawn and fine-control cadmium rods are inserted into it to a certain depth.

Violent growth of the reaction is also prevented by the U-238, which absorbs a considerable number of the multiplying neutrons.

When the U-235 in the central rod has split completely, quite a large amount of plutonium has been formed in the blanket of U-238. The blanket is withdrawn from the reactor, the plutonium formed is separated from the U-238 that is left, and a central rod is now made from this newly obtained plutonium. The reactor is operated from then on using rods made from the plutonium that accumulates each time in increased quantity in the blanket of U-238.

Whereas only seven kilograms of U-235 from every ton of the nuclear fuel charged into an ordinary reactor can be utilized to produce heat or power, in fast neutron reactors every 100 grams of burned out U-235 yields up to 120 grams of the new nuclear fuel, Pu-239; and for every 100 grams of burned out Pu-239 up to 150 grams or more of new plutonium is formed owing to the fact that U-238 turns into this kind of nuclear fuel.

After several of these cycles the quantity of the plutonium formed doubles. The surplus plutonium can be charged into a second reactor, so as to initiate a second, parallel cycle of plutonium breeding in it. Then, after several more cycles the quantity of plutonium will be quadrupled, and it will be possible to use it as nuclear fuel in four reactors. and so on.

When the first reactor of this type was started up scientists saw the magic stove that gave back two logs for every one burned!

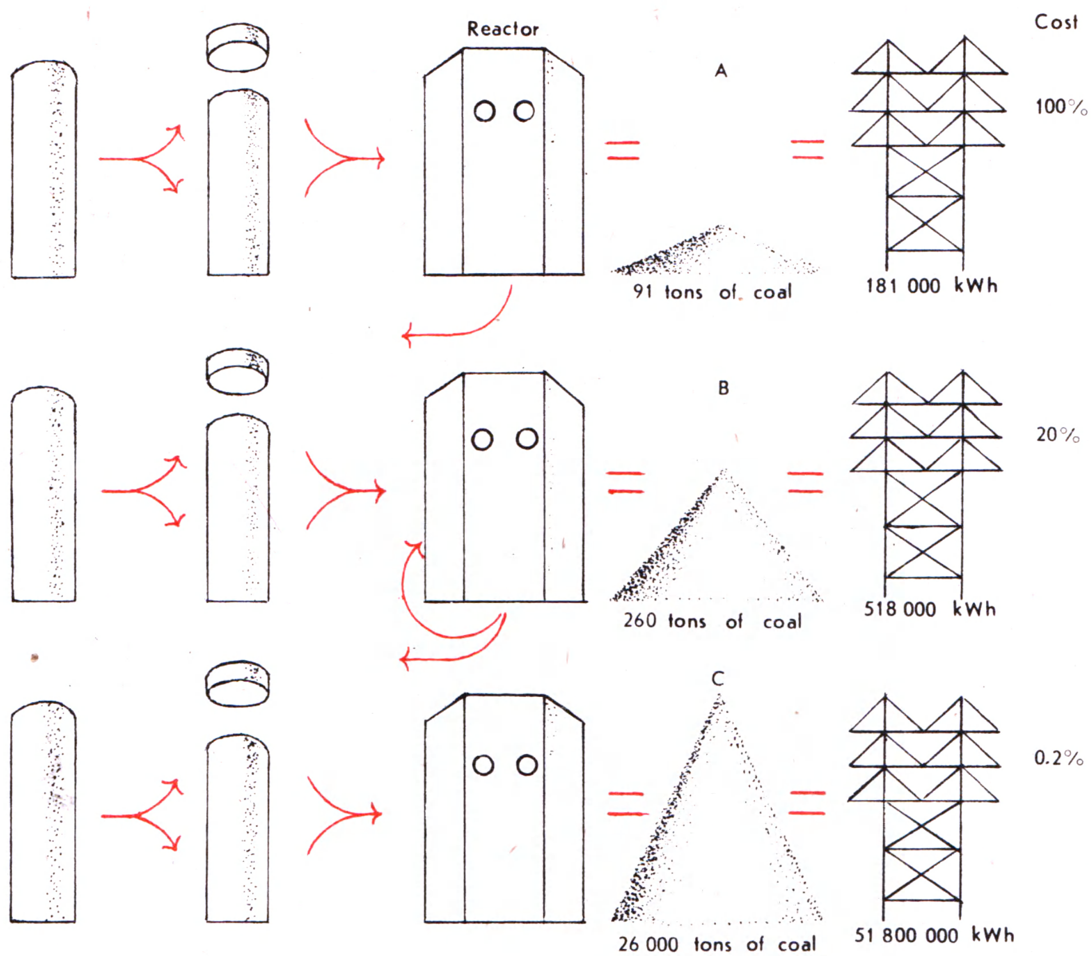
Nothing of the sort! And in fact it wasn't. But things are different in an atomic furnace.

The two extra 'logs' do not come out of thin air, of course, but from the U-238 used, which had hitherto been regarded as waste, just like the waste with wood—the bark, the twigs and leaves, the chips, sawdust, and shavings. They used to be regarded and treated as waste, not because it was absolutely impossible to utilize them, but because of the temporary lack of knowledge of how to do it.

One hundred per cent utilization of natural uranium can be achieved only by ceasing to accumulate plutonium. Plutonium must arise from the ashes in the reactor and disappear again in order to produce energy continuously. That makes a breeder-type reactor, incidentally, an ideal power and research reactor for atomic generating stations, atomic engines for ships, etc.

But it must be borne in mind that this type of reactor is still in its infancy. It is still complicated and gives much trouble in operation; and not all its advantages and shortcomings have yet been detected and evaluated. But to get an installation for the economy that enables us to increase our resources of atomic power almost 100 times is 'well worth the candles'.

The economic considerations are of great interest. Our diagrams illustrate three different types of reactor, showing the estimated cost of generating electricity with them.



Comparative characteristics of the three most important systems of reactors: *A*, ordinary; *B*, regenerative; *C*, breeder; shown at the right is the comparative percentage cost of electricity produced by means of these reactors

The first row represents a reactor operated with pure U-235. The second shows the quantity of power produced by means of what is called a regenerative reactor, using natural uranium, in which the fission of U-235 is accompanied by the formation of a rather smaller amount of plutonium from U-238. We see that the energy obtained is almost tripled, compared with the first type.

Finally, the third row shows the amount of electricity generated by an atomic power station using a fast breeder reactor in which all the natural uranium can be used up through successive cycles of reproduction.

Economically, the scheme of the third row is best. For that reason it can be said that the future of atomic power lies with breeder reactors.

The Dream Begat a Plan, the Plan a Dream

The Soviet statesman Sergei Kirov liked to say that dreams were the sketches for plans. Nuclear power engineering is a brilliant illustration to this saying.

Not so long ago, less than 30 years

back, the release of nuclear energy as the most daring and fantastic, but seemingly the most hopeless, dream of men. Yet only ten years were needed for the dream to come true and be realized in the atomic power station, and that in the country whose existence had been only a dream less than 50 years earlier.

The further progress of the dream, now incarnated in the flesh and blood of theory and practice, is accelerating at dizzy speed.

The experience gained in operating the world's first atomic power plant showed it was possible to reduce the cost of the electricity generated at an atomic power station below that of the power generated by thermal stations, provided its capacity was high enough.

In the Soviet Union, for example, two 'large calibre' atomic power stations have been built, the Kurchatov station in Beloyarsk and the Novo-Voronezh station, in both of which the first generating units were started up in 1964. The first unit of the Beloyarsk station was rated at 100 megawatts. At this station superheated steam was produced by a reactor in commercial quantities for the first time in the world, giving it an efficiency around 35-38 per cent, i.e. equal to that of the most efficient contemporary thermal power station.

The first unit of the atomic power station in Beloyarsk incorporates two circuits. Water circulates in the first circuit at a pressure of 155 atmospheres through the evaporating channels of the reactor core, just as in the first atomic power station, and there it is heated to 340°C by the fission of uranium, and partially evaporates. The mixture of water and vapour formed (emulsion) goes to a separator where the water is separated from the steam. From the separator the steam passes to a special evaporator (or heat exchanger), where it gives up heat to the water circulating in the second circuit, and then returns to the core.

In the evaporator the water of the second circuit is converted into steam at a temperature of 314°C and a pressure of 110 atmospheres. This steam does not pass to the turbines, however, but flows back to the reactor core, to special superheating channels, where its temperature is raised to 480°-500°C. Then this superheated steam is passed to the turbine blades at a slightly lower pressure of 90 atmospheres.

The second power unit of this station, rated 200 megawatts, is a further modification of this type of reactor, based on a simpler and more efficient single-circuit system.

Thus, the full power of the Beloyarsk atomic power station is 300 megawatts.

Is it possible for a reactor of the Beloyarsk type to reach the capacity of a first-class thermal power station?

It is calculated that it can if the steam temperature is raised to 535°-565°C, and the steam pressure to 250 atmospheres, which would give it an efficiency above 40 per cent.

The first unit of the Novo-Voronezh atomic power station commissioned in the same year (1964) as the Beloyarsk, had a capacity of 200 megawatts. Its reactor is a water-moderated, watercooled type with a strong pressure-vessel.

The comparatively low steam pressure in this reactor system facilitates operation of the equipment, and the station as a whole is very reliable.

When its second power unit was put into operation the capacity of the Novo-Voronezh atomic station was raised to 575 megawatts and the cost of the power generated became comparable to the general cost in that area.

The two types of reactor mentioned here can serve as the basis for building atomic power stations employing thermal neutron reactors.

We have already said how important it is to create breeder reactors, permitting utilization of not simply 0.7 per cent of natural uranium, but the whole 100 per cent of it, i.e. 150 times more.

After long research it was decided, for example, in the Soviet Union to build a first large fast-neutron reactor, rated at 300-350 megawatts, with a view of constructing others in the future of 600 and 1 000 megawatts. The future of atomic power undoubtedly lies with fast-neutron reactors combined with breeding nuclear fuel.

At least 75 years elapsed from the time it was discovered how to transmit electric power over long distances before the first generating station was built. The first atomic 'bonfire' lit in Fermi's laboratory preceded the first atomic power station, commissioned in the USSR, by only 12 years. It would therefore be naive to expect that when high-power atomic stations are commissioned all scientific and technical problems facing nuclear engineering and industry as a whole would be solved, and that all that would be left to do would be to start building of a whole series of atomic power stations, so as to replace the imperfect and obsolete thermal ones. Actually, it is far from like that. Atomic power differs so greatly from all the other forms of energy utilized by men, and its prospective uses are so vast and spectacular, while the methods and forms of using it are still so imperfect and so to say, primitive, that all we can speak about at present is the first exploratory steps in this field. Indeed, the most advanced atomic power station is a miraculous, almost magic horse (the nuclear reactor) harnessed to an old and antiquated waggon (the steam boiler), the same inevitable stage of barbarism in the history of science and technology, as the combustion of oil and coal.

And although we still do not know what will happen to nuclear power in the next ten or fifteen years, we can say for sure that it will differ greatly from everything we admire today.

Even the building of big atomic power stations for ordinary employment should be regarded mainly as experimental with a view to accumulating very important and needed experience, for after individual stations of hundreds of megawatts capacity, others will be built whose capacity will be measured in thousands of megawatts. That is why, in building a new nuclear reactor or power plant, the scientists and designers introduce new and daring features. For it is necessary, while there is the time and opportunity, to make wide-scale checks on the advisability of newly introduced elements, without for a minute holding up the planned increase in the total capacity of atomic power stations.

During recent years a whole galaxy of nuclear power installations has been created, of various types and purpose. We shall tell you about the most interesting of them.

'SP'

Those intriguing two letters mean 'superpowerful'.

In order to be able to build reactors of any conceivable, or still inconceivable, purpose and characteristics, there must be a modern, excellently equipped, and powerful scientific organization. In the USSR this is the Nuclear Reactor Research Institute of the Committee for the Peaceful Use of Atomic Energy of USSR Council of Ministers, which is located in the town of Melekess, in the Ulyanovsk Region. It is a special pro-

ving ground and pilot plant for nuclear power engineering. Here various systems for atomic generating stations are developed and tested, and also the various materials used in nuclear engineering. Naturally, being the main research centre, the institute must have the reactor of reactors, and such a one was built by its scientists.

The Ulyanovsk atomic power station is a most important direction in new quests. It employs a 'boiling water' reactor that converts the water supplied to its core into high-temperature and high pressure steam that is passed directly to a turbine. But there is also provision for operation on the system adopted at the Novo-Voronezh atomic power station, by which the water, heated to 309°C, is passed at a pressure of 200 atmospheres to a steam generator where it gives up its heat to the second circuit, the water of which evaporates into steam at 237°C, and 32 atm, which drives the turbine.

The capacity of the Melekess power station, it is true, is small, only 50-70 megawatts, but it does not need more. But for the research work conducted there neutron fluxes of as high an intensity as possible need to be available; and it is very difficult to provide that since it is necessary, among other things, to eliminate thousands of seemingly trivial and immaterial obstacles.

First of all designers succeeded in ensuring proper cooling of the reactor core, and in selecting structural materials of a comparatively low neutron-absorption capacity, but able to withstand high temperatures.

Neutrons of all energies from the fast to slow (thermal) are released, as we know, in the core of a reactor, but fewest of all thermal neutrons. So it was therefore decided to leave a space filled with water or some other similar moderator in the core. When fast and intermediate neutrons penetrate the moderator, they are slowed down to thermal energies with the result that the reactor produces a very powerful flux of neutrons of an intensity measured by a figure with fifteen noughts, 10^{15} neutrons per square centimetre per second. (Incidentally, the most intense flux of neutrons so far produced in the USA is 4.2×10^{14} neutrons per square centimetre per second.)

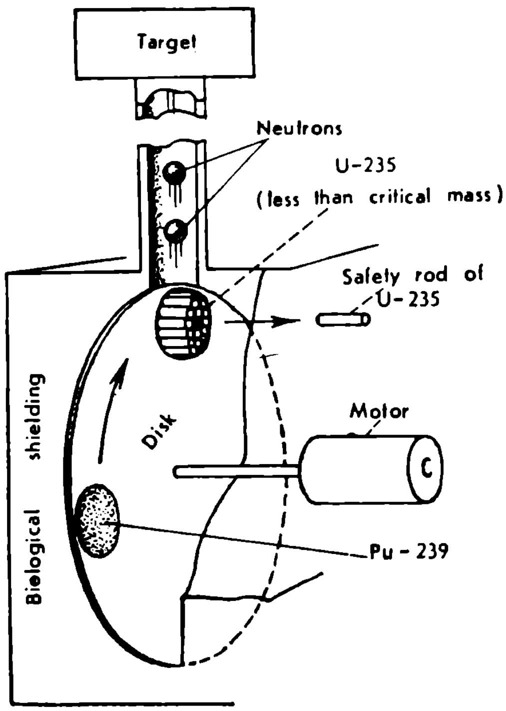
The core consists of fuel elements, each representing a packet of fuel plates. The water used as a coolant is forced through slits in the plates at a pressure of 50 atmospheres. Since some of the irradiated water decomposes into hydrogen and oxygen, forming detonating gas, the reactor incorporates a special system by which this very dangerous gas is turned back into water without an explosion.

For the first time the fuel elements of the reactor core are replaced by means of a special automatic fuel-charging machine, that also extracts spent fuel elements and recharges the core with new ones. The fuel elements are stored nearby, in a special storeroom.

The body of the reactor is pierced by a great many holes and channels which are used for exposing investigated substances to neutron fluxes of various energies and intensities, and also special holes for extracting beams of neutrons from the reactor for physical research in special premises. Control of the reactor, of course, is fully automated.

'Teaser'

A nuclear power reactor should have the following main points: reliability and long service-life; easy control; high but not extreme operating characteristics or parameters, and a 'reserve'; full safety for staff. Nothing should be pu-



The working principle of a fast-neutron pulsed reactor

shed to the 'brink', although it is practically impossible for an ordinary reactor to become an atomic bomb and explode during operation, since the atomic fuel is dispersed in it and, because of that, the rate of increase in the intensity of the chain reaction, even in the event of serious breakdown, will not lead to an explosion. In addition, as the temperature in the core rises, the rate of the chain reaction drops sharply.

But there is an extraordinary number of temptations to run the chain reaction at 'five to midnight', just a little short of an explosion. Such a high rate means fantastic quantities of released heat, only limited by the capacity of the coolant to remove it, and by the ability of the structural elements and fuel elements to stand up to the high temperatures and bombardment by the powerful flux of neutrons, snowballing as the rate of the chain reaction rises. And scientists are in ever increasing need of great fluxes of neutrons, in order to investigate the very interesting and important changes that take place in various substances during neutron bombardment, beginning with the 'cold' processes of increasing the yield of valuable products from petroleum or vulcanizing rubber, and ending with the destruction of cancerous tumours in the human brain almost inaccessible to the surgeon's scalpel.

But how can a chain reaction be run at a 'pre-explosion' rate?

You already understand the principle of the atomic bomb. All that is needed is to bring two hemispheres of U-235 or Pu-239 together rapidly or rather to 'shoot' them against each other, with each of the two hemispheres deliberately made of subcritical mass. The resulting chain reaction is explosive and lasts a millionth of a second after the two hemispheres come into contact with each other. And although it is still possible to control a chain reaction somehow immediately it begins, it becomes very soon uncontrollable.

But now there is a reactor that not only makes the impossible feasible, but does so quite safely.

Imagine two lumps of plutonium of a mass a little less than the critical mass. The two lumps are placed opposite one another so that there is a gap between them, sufficiently wide to preclude a chain reaction beginning. In this gap a disk with a block of U-235 attached to it rotates at a speed of 5 000 revolutions per minute. During the fleeting moment that the piece of uranium flies through the gap and between the two lumps of plutonium, the whole mass of the nuclear fuel becomes supercritical, and an explosive chain reaction begins in it ... . But no explosion occurs, because a tiny fraction of a second before the explosion can begin the uranium

flies out of the gap, and the chain reaction ceases just as rapidly. During the moment of 'opposition' of the plutonium and uranium a very high-energy beam of fast neutrons is ejected like a flash of lightning. And that is impossible with even the largest industrial reactor.

Well, but what if by some awful chance the lump of uranium got stuck between the deadly lumps of plutonium?

That is impossible for purely mechanical reasons. But just to be dead sure in any case, and to increase safety of operation tenfold, the lumps of plutonium are not solid, but made up of individual thin rods, like a bundle of pencils. In the event of failure of any kind, or if the rate of the chain reaction rises above the admissible level, an automatic quick-response device operates, knocking one or two 'pencils' out of the pack, so that the total mass of plutonium and uranium becomes less than critical, and a chain reaction cannot begin in it.

The main value of such a reactor is the fact that with an average power level not greater than 1 000 watts, it 'shoots' out neutron pulses 5 000 times a second, each pulse corresponding to the neutron flux of a reactor rated at several million watts (megawatts).

Five thousand times a second the human hand deliberately 'almost' explodes an atomic bomb, and interrupts the explosion as many times, bending it to man's will. It is not without reason that the scientists who created it, jestingly and lovingly call it the 'teaser', although its full official title is 'impulse fast reactor'.

All its parts and associated equipment, of course, where there is even the slightest possibility of the neutron beam breaking outside, are surrounded by reliable walls of biological shielding.

'Arbus'

The power of this atomic electric generator is low, 'only' 750 kilowatts. But its main advantage is not its power, but its light weight, for it is designed for remote localities deep in the northern tundra, or the dense forests of the bush or taiga, in uninhabited territories, and other remote regions still without power transmission lines, supplying them with life-giving energy, heat, and light.

The main weight of an atomic generator operating on a water-vapour cycle is not that of the reactor itself, but of course that of the biological protection, since it is necessary to shield not only the reactor core, but also all parts of the primary circuit, including the coolant, piping, pumps, heat exchanger, etc. Only the water and the pipes of the secondary circuit and the turbine can be left without biological shielding.

The reason for this is the water. In flowing through the reactor core, it absorbs radiation and becomes strongly radioactive and so extremely dangerous to man.

But let us see what would happen if the water were replaced by a substance that did not become radioactive when exposed to radiation of any intensity.

The designers of 'Arbus' tried a bold innovation. They replaced the water in the first circuit by an organic coolant, quite 'indifferent' to radiation. This liquid not only removes heat well from the core, but it does not become activated, i.e. it does not become radioactive. The rival of water and of liquid metals turned out to be gas-oil, ordinary diesel fuel. All it required was careful filtering before employment in the reactor in order to remove impurities, especially sulphur, that would easily become radioactive upon irradiation.

So you see, in this device the 'ato-

mic fire' is quenched with an easily inflammable fuel.

But the gas-oil, having passed through the reactor core, remains as safe as when it entered. So almost none of the components, except the reactor itself, or rather the core, require biological shielding. In addition, gas-oil is not corrosive, so that all pipes, pumps, and accessories (fittings, valves, etc.) can be made from ordinary steel.

But that is not all by a long chalk. Because of the high specific heat of the coolant, its operating pressure is 20 times lower than that characteristic of atomic power stations with water-cooled reactors. The only drawback of this coolant is that it is polymerised by radiation, i.e. turned into a plastic. In consequence used gas-oil must be purified of the products of the chemical reactions it undergoes when used as a coolant.

All this electric generator requires for a year's operation is several tons of fresh gas-oil and two kilograms of uranium. With ordinary diesel engines such a generator would need about 1 500 tons of diesel fuel. But one uranium charge lasts 'Arbus' for two years.

But let us get back to where we began. 'Arbus' weighs altogether 360 tons. The comparatively small volume of biological shielding made it possible to divide it up into 19 individual units, none of which weighs more than 20 tons, so that it is possible to deliver it to any place in the country.

And in spite of all the features described and departures from common practice, 'Arbus' is simple and reliable in operation and convenient to use.

Self-Propelled Atomic Generator

If you think the creation of 'Arbus', the superlight atomic power station was wonderful, then you will find another one with the very modest name, TES-3 (Thermal Electric Station-3) even more remarkable. It is difficult for anyone used to seeing an atomic power station surrounded with huge strong concrete structures, to believe that four cross-country transporters mounted on wide crawler tracks can house and carry a mobile 1 500-kW atomic electric generator. It can be used in areas where it is impossible to bring even the light 'Arbus', where there are no railways or landing strips, but where there is a desperate need for power.

The 'TES-3' is taken to the nearest point on four open railway wagons, or by steamship, then it can be driven on its own tracks across hundreds of kilometers of rough country, negotiating metre-high obstacles like a tank.

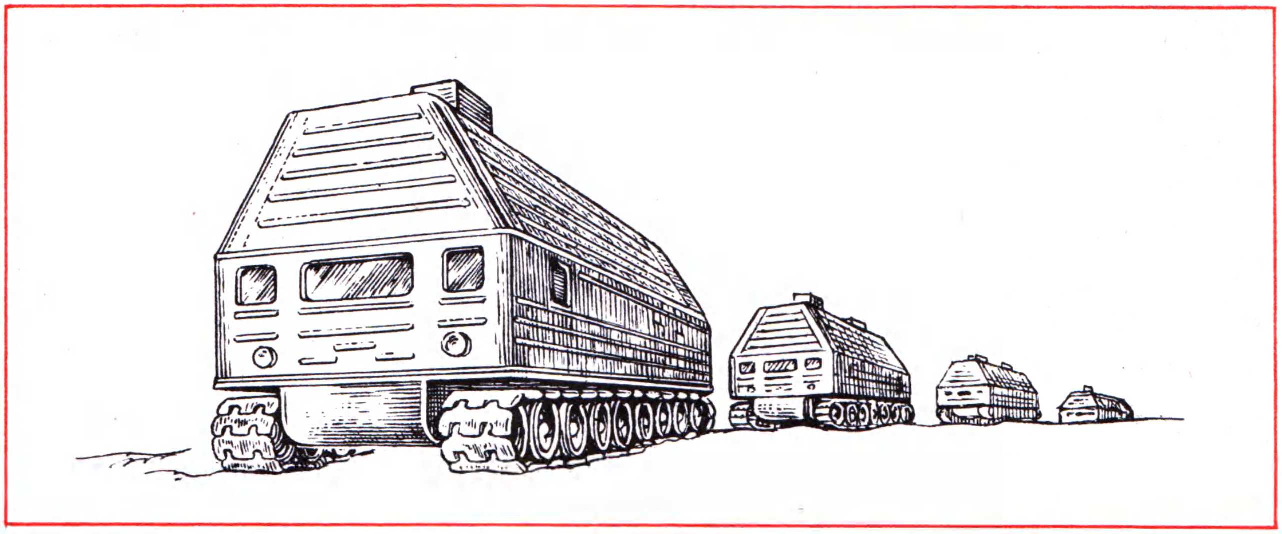
When it reaches the place where it is to be used all the units are connected up by pipes and cables. It is also necessary to build a shelter for the first two vehicles, a special trench with a thick concrete floor and roof and covered over with a thick layer of earth. The station is then ready for operation.

The first of the cross-country vehicles accommodates the atomic reactor, and the second the circulating pumps, steam generators and other equipment of the primary, radioactive circuit. The reactor and generating equipment usually operate on a water-water cycle.

Water circulates in the first circuit at a pressure of 130 atmospheres, and steam, heated to 280°C, fills the second circuit from the heat exchanger to the turbine. An ordinary steam turbo-generator is mounted in the third vehicle while the fourth houses the automatic controls.

This mobile 'camp' needs a crew of only three or four men per shift. It can be kept in operation for a year without recharging with uranium as it consumes only 14 grams of U-235 a day.

The four cross-country vehicles weigh



a total of 350 tons. Two weeks after the reactor has been shut down, the station can be driven to a new site, with the radioactive fuel elements left in the reactor.

'Romashka'

Notwithstanding the enormous advances made in broadening the power base of human society, especially after electricity had been placed at the service of people, scientists were bothered for a long time, and have seriously troubled during recent decades by the formerly progressive but now very wasteful methods of consuming natural power sources like coal, oil, and other kinds of fuel.

Historically, the development of electrical engineering has followed the now conventional pattern of power generation, i.e. fuel—steam boiler—steam engine (or turbine)—electric generator, and not the simpler scheme of heat—electricity.

There were many reasons for that. The longer and more complicated method offered higher efficiency, 6 or 7 per cent in the locomotive, for instance, while all other shorter schemes of conversion did not yield more than 1 or

Self-propelled atomic power station

2 per cent. That predetermined the development of electrical engineering over two centuries, or more.

But gradually, through the efforts of engineers and scientists, the efficiency of using the thermal energy hidden in fuel increased to 25-30 per cent, and the efficiency of present-day power stations is as high as 35-38, even 41 per cent.

Almost no attention was paid, naturally, to the development of other, better and more efficient methods of converting thermal energy into electricity.

But the fuel reserves of mankind became threatened as the annual output of coal in the whole world rose to 3 000 million tons, and of oil to 1 500 million tons, not to mention natural gas, plant fuels, and other kinds—altogether nearly 5 000 million tons. And there is no disputing that the reserves of fuel are diminishing in a disastrous way, both absolutely and in relation to the rise in output. Opinions vary only as to how long the reserves of coal and petroleum will last. Some people believe there is enough coal for the next 300 or 500 years and of petroleum for 50 years,

but others cut these estimates to a half or a third as long.

In the light of the inevitably approaching fuel shortage, it seems a crime to extract 5 000 million tons of fuel per annum, and blow three-quarters of it literally to the wind. It is hardly likely that there is any other branch of human activity in which natural resources are utilized with as low an efficiency as in power engineering.

So it is not surprising that whole armies of scientists all over the world have attacked the problem of direct conversion of heat into electricity without intermediate processes. Very soon it became clear that certain methods of generating power directly from heat, discarded at the very dawn of power engineering as having no prospects, have proved in the light of the latest advances of science to be far more promising than the methods that dominate power engineering today.

Without going deeply into the principles of these 'new' methods, many of which are known to science for over 100 years, we shall only mention them here.

One is the method of converting sunlight into electricity which promises in due course to reach an efficiency of 45 per cent. Then there are the thermionic devices with an efficiency of 65-70 per cent; the magnetohydrodynamic generators with an efficiency of the order of 70-80 per cent; thermogenerators with an efficiency at least 45-50 per cent; and, last, chemical fuel elements, promising an efficiency around 100 per cent, while even the theoretically possible efficiency of thermal power stations has a ceiling of 41-43 per cent.

Taking into account the fact that all over the world power is generated by means of a tremendous number of electrical devices of existing types and kinds, it will take several decades, perhaps many, to replace them all by plant of the 'new' kind.

Atomic power by itself promises to eliminate or postpone the coming power hunger for ages, perhaps for thousands of years. But even it is open to criticism for its low efficiency, since efficiencies of 41-43 per cent are attained only with great difficulty.

It is, therefore, not surprising that in developing atomic power stations of all kinds scientists should not ignore the fact that they were harnessing a fiery steed, an ultramodern nuclear reactor, to an old cart, the steam boiler, and not to something new, and promising in principle higher efficiency.

We needed that long introduction in order to underline the importance of the first step taken by Soviet scientists, on 14 August 1964, when they brought into operation a new experimental unit for direct conversion of nuclear energy into electricity. This unit was given the lyrical name 'Romashka' (Daisy), for its outward appearance resembled that flower.

More than a century ago it was observed, that if pieces of two different metals were joined together, and one of them was cooled and the other heated, an electric current would flow through the circuit formed. For a long time this phenomenon was only used in measuring instruments, because of its low efficiency (around 0.5 per cent). Present-day semiconductor techniques have made it possible, however, to produce materials in which heat can now be converted directly into electricity with an efficiency of 10-11 per cent.

Since a nuclear reactor is by nature a heat engine, its use as the source of heat for thermo-electric conversion of energy is most promising.

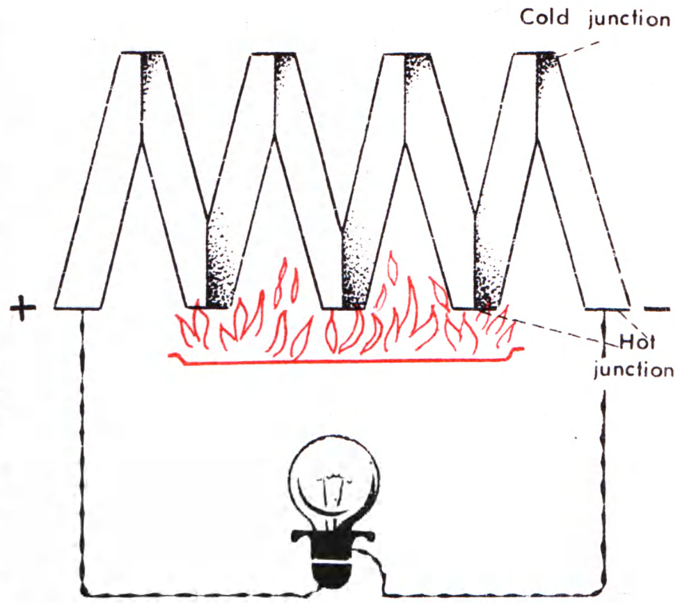
In the experimental 'Daisy' reactor-converter the heat released in the core of the high-temperature reactor heats

the 'hot' junctions of a large number of batteries built up from thermo-electric elements that convert it directly into electricity.

Heat is released in the core of the reactor, which is a cylinder charged with 11 graphite fuel assemblies containing plates of uranium dicarbide. The fission reaction is induced by fast neutrons. The reactor core is surrounded on all sides with a beryllium neutron reflector.

Since the efficiency of thermo-elements rises as the difference in the temperature of the hot and cold junctions increases the temperature at the centre of the core reaches 1 170°C.

The thermo-electric converter, which is built into the external surface of the reflector, has a temperature of about 1 000°C. It consists of semiconductor thermo-electric elements made of a silicon-germanium alloy. One side of the elements is heated by the heat released in the reactor, while the other side is cooled. The thermopile or atomic heat battery generates a current of 88 amperes, which is drawn off into the external circuit.



The principle of the semiconductor thermo-electric battery used in 'Daisy'. Each thermo-cell consists of two semiconductors, differing in the sign of the thermo-electric effect produced. Their heated ends are soldered together to form a hot junction. The hot end of one of the conductors is positively charged, like the cold end of the other. The difference in potential arising between the cold ends or junction of each thermo-cell (or couple) is about 0.2 or 0.3 volt at a current intensity of up to one ampere

The output of 'Daisy' is still low, 500 watts. But we must remember that it is the first operating installation of this type. It will take some time to get enough experience to design the lightest possible, compact power stations for various purposes of all kinds.

Atoms to Irrigate Deserts

More than two-thirds of the Earth's surface is covered by the oceans or, to put it simply, by water. It would even be more appropriate to call our planet Water, for example, or Oceania, instead of Earth.

But nearly half of the third occupied by land consists of deserts, semi-deserts, and arid areas. And Nature has not made even the rest 'comfortable' for man.

There are the over-wet, cold, harsh, thinly populated northern areas with many rivers, lakes, marshes, and bogs and the vast amounts of frozen water covering the Arctic and Antarctic regions and there are the densely populated southern lands, burning with thirst, that could be turned into a paradise at the wave of a wand if they could be irrigated with enough water. And what makes it even more tragic is the fact that many of these areas lie cheek by jowl with the boundless wastes of the oceans and seas.

But sea water is bitterly salt. It cannot be used to quench the thirst of either people or land.

The Soviet Union, for example, has the biggest reserves of fresh water in the world. But, just as in other parts of the globe, they are not distributed uniformly. About 80 per cent of the water is found in the north and east, where only 20 per cent of the population and productive forces (factories and farms) of the country are located, while in the areas where the remaining 80 per cent of the population live and the bulk of industry and farm lands are located, there is little water and much desert and arid land. But there was a time when they too were among the most flourishing and fertile areas on Earth.

For centuries man has waged a stubborn struggle against the advance of the desert, against the burning sun, and the hot wind. But he has been continually forced to retreat, for he lacked the means and forces to hold his powerful antagonist in check. Only his own hands and the muscle power of domestic animals—that was all!

And only the modern, socialist society of the USSR, with its powerful machines and industries has been able to tackle the age-old enemies of the farmers of these areas. In this struggle the main weapon is water. Soviet people have begun to build artificial seas filled with fresh water, to build canals, thousands of kilometres long, and to reverse the flow of rivers, directing them to areas that dried up ages and ages ago.

But this water must be won, usually at a high price. So naturally, people had an idea. Would it be possible to take salty sea water or underground waters, of which there is an abundance almost everywhere, especially in the south, and turn them into fresh water? Not just a cup of water or a bucketful, but whole rivers that would bring water to hundreds of thousands and millions of people, give life back to fields, and orchards, and forests.

Salty water can be made fresh (or desalinated) in many ways. One way, for instance, uses certain new artificial materials, called ion-exchange resins. When water is passed or filtered through a great many thin membranes made of these ion-exchange resins, the salt dissolved in the water can be separated out and removed. Or water can be frozen; the salt concentrates in the bottom part of the block of ice, and fresh water at the top. And another way is simply to heat and evaporate the water, collect and cool the vapour, now free of salt, and condense it back into water, that will now be fresh.

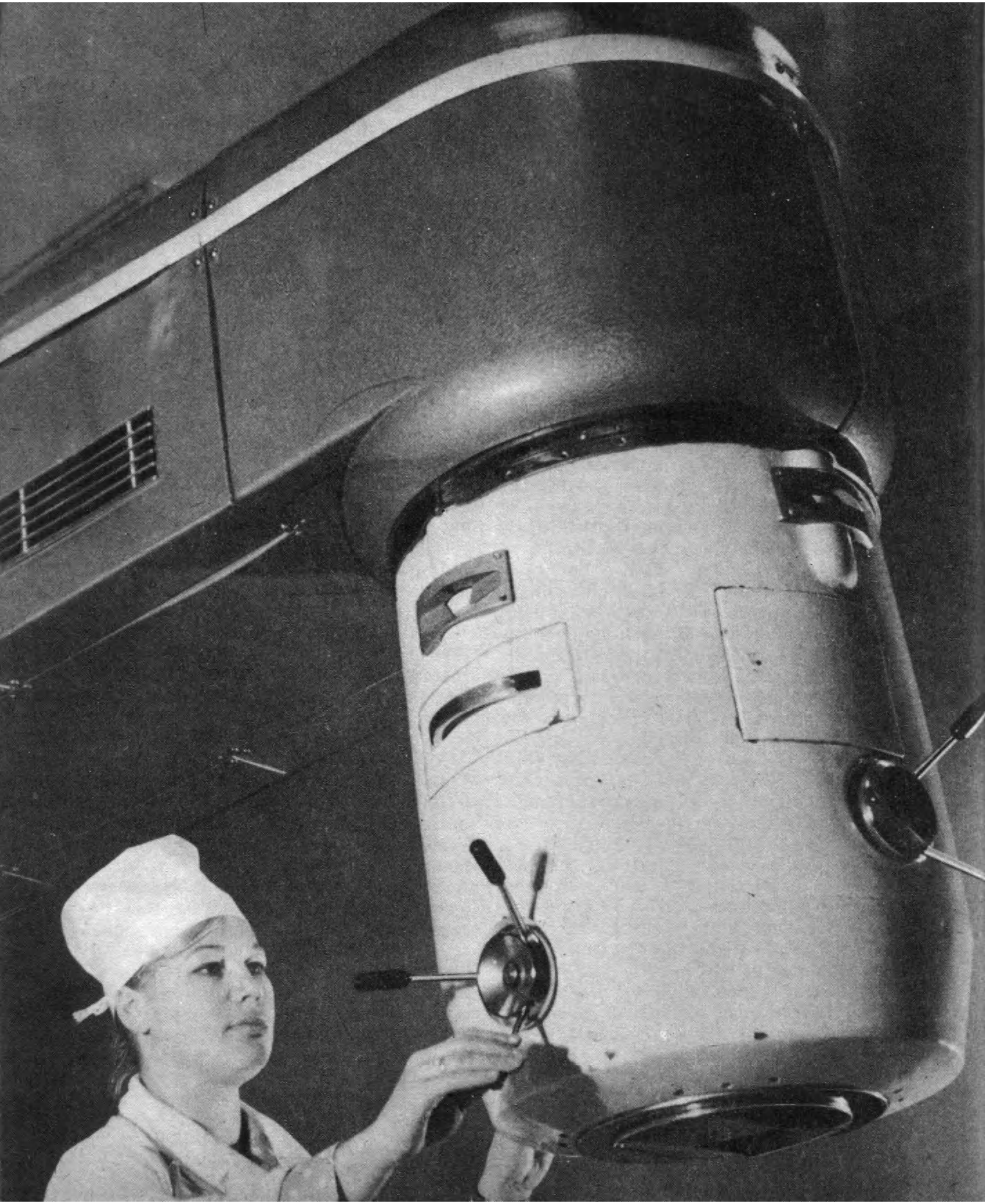
But all these methods call for great expenditure of money and materials, and tremendous amounts of power. A desert is not simply a place where rain does not fall but is also a place where there is no power. It has been calculated that it would be necessary, in theory, to consume a minimum of one kilowatt-hour of power to obtain a ton of desalinated water. But where is such power to come from? Does even a powerful, developed industrial country like the Soviet Union have the forces to cope with this problem? For it would take thousands of millions of tons of fresh

water to irrigate all its deserts and arid regions properly.

Such a force has been found. It is the energy locked up in the atom. If a very high-power nuclear reactor is used for this purpose, the power produced will be much cheaper than that generated by ordinary thermal power stations.

An atomic power station, burning no more than two kilograms of uranium or plutonium a day, could supply not only heat for evaporators or cooling units, but also sufficient electricity for a big industrial city or an area with a population of a few hundred thousand people. Both power and water!

The first plant of this kind, with a capacity of over a million kilowatts has been built on the east coast of the Caspian Sea in the town named after the famous Ukrainian poet and patriot Taras Shevchenko. The heat obtained is used to work a generating station rated at 150 megawatts, while the waste steam will be used in a desalination plant that will produce 100 000 to 110 000 cubic metres (or tons) of fresh water a day at a cost of around six kopecks per cubic metre. Such a quantity of water will be enough to supply a town with a population of 20 000 or 30 000 people.



Chapter Eleven

THE 'YOUNGER' BROTHER OF ATOMIC ENERGY

What Does a Capful of Smoke Cost?

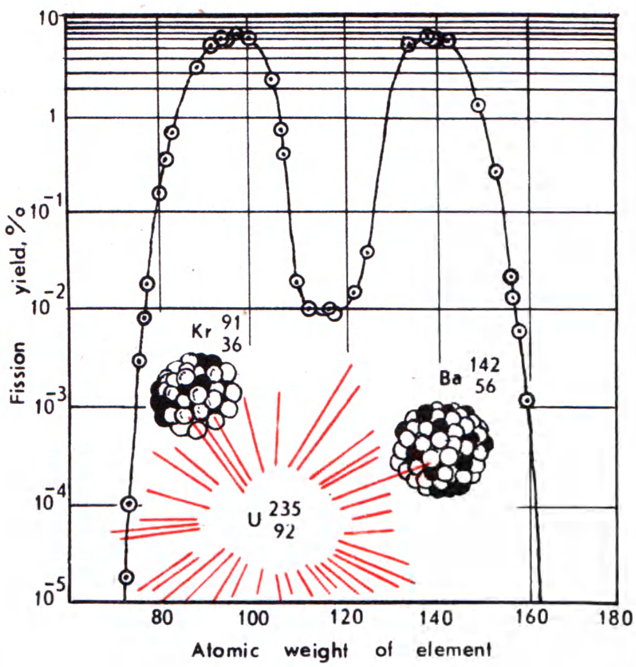
There is a story that at the beginning of this century, the owner of a big English steelworks was visited by the representative of a chemical company who offered to buy, guess, the smoke that hung over the works all the time in a thick blanket and made the life of the workers and people living round about miserable. The owner willingly signed a contract giving the strange buyer all the smoke coming from the works for free of charge for a period of 99 years, while the buyer undertook in turn to pay the cost of building all the smokestacks and chimneys in the works.

The extraordinary deal was the laughing stock of newspapers and humorists for a long time. No jokes and gags were missed to describe the vessel in which the buyer carried off his precious purchase, and what was the current market price of a capful of smoke.

Before long the buildings of a chemical works sprang up near the steelworks, and in a few years the owner of the latter was tearing his hair for his stupidity and lack of foresight. His enterprising neighbour, having organized the extraction of the extremely valuable substances carried off in the smoke, began to enjoy a profit almost as great as that received by the steelmaster without much effort or special outlay.

For the weightless, unwanted and even harmful. smoke contained a host of things, from sulphuric acid to platinum.

Something like that also happened in the atomic age. The 'ash' formed by the burning up of the nuclear fuel, i.e. the fission products of U-235 and Pu-239, which in essence are the wastes of nuclear reactors, have found wide application in science, engineering, and industry today. In Moscow there is even unusual shop with sign 'Isotopes' on its front.



The kinds and quantities of radioactive 'waste' resulting from fission of U-235

When a certain quantity of U-235 undergoes fission in the course of a chain reaction, it yields about 250 new elements ranging in atomic weight from 72 to 162. The drawing at the top shows their distribution according to atomic weight or mass, and the approximate quantities of each of them; while the Table gives the most important of them. Some vanish rapidly, passing at once into a stable isotope. And we can say for certain that only a comparatively few of long-lived radioactive elements are formed in considerable quantities of any kind.

In an atomic power station with a power of 100 megawatts between 90 and 140 kilograms of these isotopes are formed in a year.

The radiation activity of isotopes is generally measured in units, called *curies*, which is the amount of radiation given off by one gram of radium in one second. Each kilogram of the radioactive products formed in an atomic power station during operation corresponds in radioactivity to about 2 000 kilograms of radium. To appreciate the stupendous magnitude of that figure, let us recall that the total world reserve of radium in the first forty years of this century was scarcely more than two or three kilograms!

Unlike natural radioactive substances, these fission products do not emit alpha-particles. But, even the few radioactive isotopes listed here are quite sufficient to show what wide application they find in science, engineering, medicine, and industry. Researchers can select suitable isotopes that emit only beta-particles, or only gamma-rays, or both.

For each kind of radiation it is possible to select an appropriate energy, varying between around 30 000 and 150 000 electron-volts and beta-particles of very high energy, of the order of 3.0-3.5 MeV. And finally, isotopes can be selected with half-lives varying from seconds to several years depending on their use.

A general rule can be noted here: short-lived isotopes mainly have the highest intensity of radiation. We shall come back later to some of the special features of radioactive isotopes, their main characteristics.

In spite of the relatively diverse properties of the radioactive isotopes obtained from the fission of U-235, modern science and technology have reached such a level that they have already become insufficient. Biology, medicine, agriculture, chemistry, and many other fields need radioactive isotopes that are not found among uranium fission products at all, or only in the tiniest quantities. Metallurgy, for instance, and certain branches of medicine need isotopes with gamma-radiation with an energy much greater than that of uranium fission products.

The Most Important Fission Products of U-235

Isotope	Chemical symbol	Amount formed (percentage)	Half-life	Types of radiation and energies, MeV: Beta-particles	Gamma-rays
↓ Strontium-90	Sr	5.3	25 years	0.61	None
Yttrium-90	Y		62 hours	2.3	None
Yttrium-91	Y	5.4	57 days	1.53	None
↓ Zirconium-95	Zr	6.4	65 days	0.39 (98%) 1.0 (2%)	0.7 (93%) 0.2 (93%) 0.92 (7%)
Niobium-85	Nb		35 days	0.15	0.76
Technecium-99	Tc	6.2	10^6 years	0.3	None
↓ Ruthenium-106	Ru	0.5	1 year	0.03	None
Rhodium-106	Rh		30 seconds	3.5 (82%) 2.3 (18%)	0.5 (17%) 0.73 (17%) 1.2 (1%)
↓ Caesium-137	Cs	6.2	33 years	0.5 (95%) 1.19 (5%)	None
Barium-137	Ba		2.6 minutes	None	0.66
↓ Cerium-144	Ce	5.3	290 days	0.35	None
Praseodymium-144	Pr		17.5 days	3.0	0.2 1.2
Promethium-147	Pm	2.6	4.4 years	0.22	None

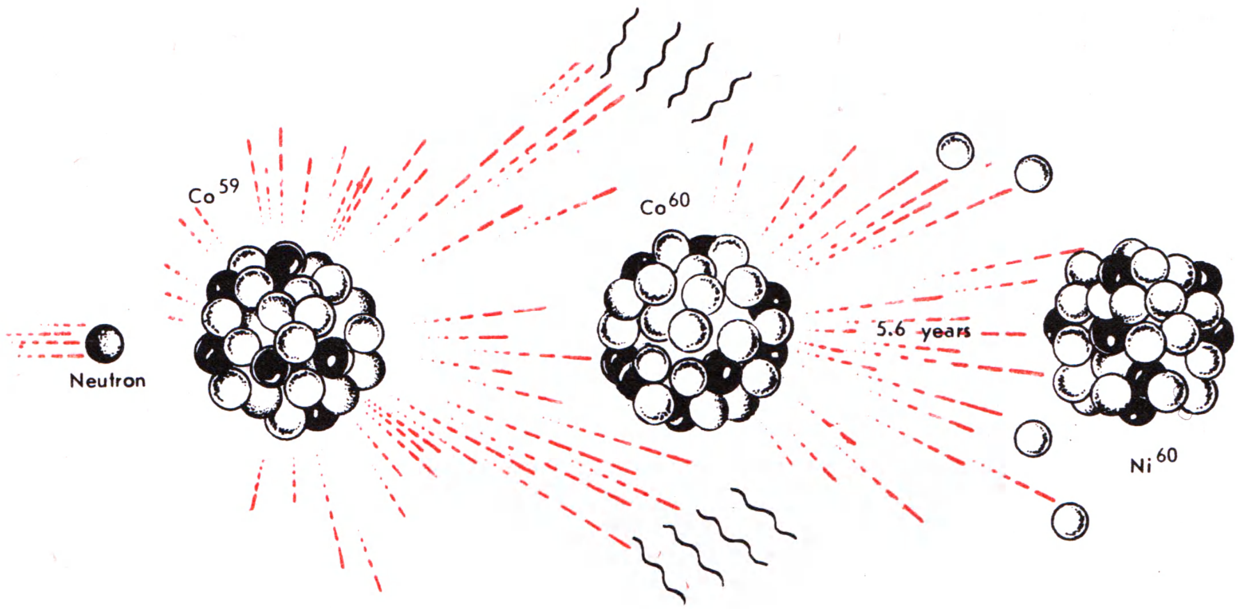
Notes: 1. The arrows on the left indicate that another element, a daughter product, is formed at the same time.
2. The nucleus of barium-137 is in an excited (unstable) state, and passes into its ground state only after emitting a gamma-quantum.

So it became necessary to look for ways and means of creating the radioactive isotopes of higher energies so needed in science and engineering. One of the most common methods of producing such substances is to expose ordinary inactive isotopes to a high flux of neutrons in a nuclear reactor.

Thus, ordinary cobalt-59 is used to produce a very widely used artificial radioactive isotope, cobalt-60. For this purpose slugs of cobalt-59 that have first been given the necessary shape are put into a nuclear reactor. Having absorbed a neutron the cobalt nucleus turns into its unstable radioactive isotope, cobalt-60. The latter is a source of weak beta-particles and high-energy, penetrating gamma-rays (1.16 and 1.30 MeV). The half-life of cobalt-60 is quite long, 5.3 years, so that it is widely used in various industries.

Precious Waste

In order to talk about the industrial uses and applications of radioactive isotopes, we would need to describe the fundamentals of many branches of modern science and technology. The fa-



$$Co^{59}_{27} + n^{1}_{0} \longrightarrow Co^{60}_{27} + \gamma \longrightarrow Ni^{60}_{28} + e^{-}$$

When cobalt-59 absorbs a neutron it turns into a very radioactive substance, cobalt-60

mous American physicist W. Libby once joked, not without reason, that one could think of at least two possible applications of radioactive isotopes every five minutes.

Here we shall only tell about what we think are the most interesting applications of these substances in a few fields.

The first is *protection against electric charges*. We have already said that various substances become ionized when exposed to radioactive radiation. Gases, for instance, become conductors, a property that is the operating principle of a number of measuring instruments.

This property of radioactive isotopes is also used in devices whose purpose is to eliminate dangerous electrical charges.

On a dry day when you comb your hair with a plastic comb you will hear a light crackling sound. And if you do it in the dark you will see beautiful violet-yellow sparks. Your comb and hair have turned into an electrostatic machine generating electric charges of quite high voltage.

If a similar electric spark is made at the exact moment in a motor car (or internal combustion) engine it will ignite the petrol vapour compressed in the cylinder and so perform useful work. But sometimes these beautiful, innocent sparks can cause serious accidents.

The very fine dust that usually forms in flour mills and sugar refineries can explode with the force of a powerful bomb and destroy huge reinforced concrete buildings.

And how much trouble is caused in mills and factories producing or using large plastic sheets or wrapping paper through their rubbing together and becoming electrically charged, or in textile mills through the rubbing of the

threads in the looms and the endless webs of cloth running to various departments. If these tiny charges are not eliminated they can cause chaos in automatic machinery and apparatus. They can cause charged surfaces to cling tightly together or, on the contrary, to spread apart, while dust particles and dirt of all kinds are attracted to the surfaces, spoiling the material produced.

It is sufficient, however, to put a beta-source (strontium-90 or promethium) near such continuously charged materials and products, a radioactive source that presents no danger to the staff, for the picture to be changed at once.

The beta-particles penetrating the surrounding air in all directions ionize and turn it into a conductor, so that the electric charges being formed are earthed at once, and so cannot accumulate in sufficient quantities to produce a spark.

Everything that for any reason becomes electrically charged discharges immediately in the presence of a radioactive source.

Another field is *radiography*. X-rays have been used for a long time to inspect various objects in order to detect possible internal flaws. But until recently, the X-ray apparatus available was of comparatively low power; the anode voltage of the tube did not usually exceed 30 000 to 75 000 volts, which was quite insufficient in a number of purposes.

The special high-voltage apparatus with a tube voltage of 100 000 and 250 000 volts, however, was only suitable for inspecting comparatively thin metal items. And X-ray apparatus with a power of a million volts or higher that could be used to inspect massive articles proved so complicated and costly that there are literally only one or two in use even now.

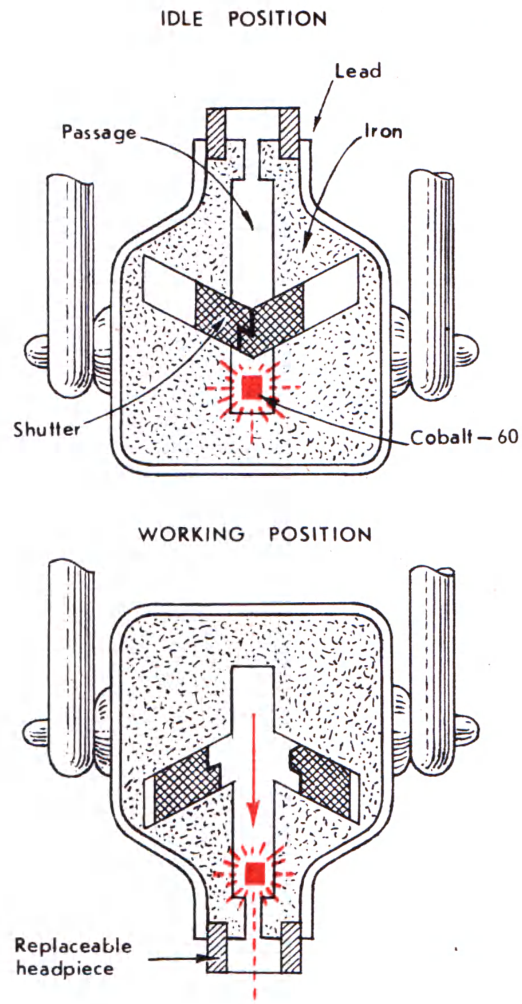
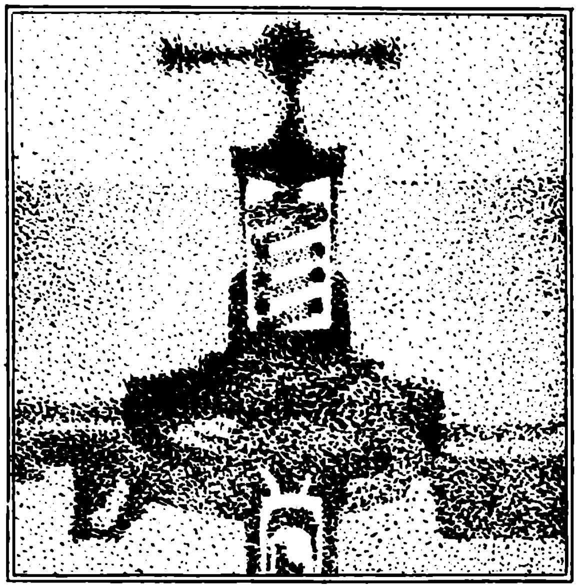


Diagram of the arrangement of one type of cobalt 'gun'



Drawing showing what is revealed on a typical photograph made by means of gamma-rays

An extremely simple way out of this situation was found when the radioactive substances produced in nuclear reactors came to be used in this field. They cost much less than X-ray apparatus, and possess sufficiently intense radiation.

It is comparatively simple to produce radioactive cobalt-60 and it is cheap. Its rays have a penetrating power equal to that of the X-rays that can only be produced by means of huge and complex apparatus operating with anode voltages around two million volts.

Cobalt-60 makes it easy to inspect steel up to 150 millimetres thick, and sometimes up to 250 millimetres thick. It is convenient to employ since, for example, the products to be inspected in a works can be left all night exposed to the rays emitted by the cobalt source. The next morning the inspector will have photographs available of the interior of the item.

The structure of one of the types of a cobalt 'gun' is interesting.

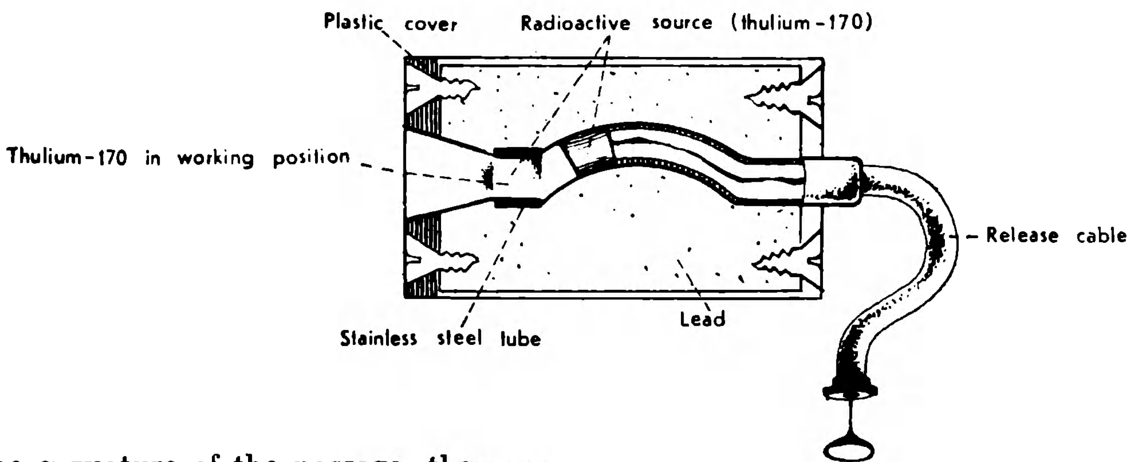
When kept in the idle position (neck upward), the thick-walled casing of the gun is the container for one or more slugs of cobalt-60. All that is needed to put the apparatus in the working position is to rotate it, so that the neck points down. The cobalt source then slides down into the neck of the 'gun' through a special channel, and two thick lead shutters open in front of it by gravity. The gamma-rays emitted by the cobalt are directed at the item being inspected, behind which a casette with a film sensitive to gamma-rays has been put.

Our drawing shows the picture obtained on a typical photograph taken by such apparatus. The places where the metal is thinner absorb fewer gamma-rays and appear darker on the plate.

The main advantages of radiographic inspection are exceptional flexibility and ease of handling of the unit. To illustrate, let us consider the pocket-size unit shown on page 190, which is as strong as a big X-ray apparatus.

It consists of a lead cylinder, 115 millimetres long and 50 millimetres in diameter, in which there is a curved axial passage 3.5 mm in diameter. This passage freely accommodates a small aluminium cup about 10 mm long. At the bottom of the cup is a round plate 0.25 mm thick made of artificial radioactive thulium-170. When a cable release like that on an ordinary camera is pressed the cup and thulium source are pushed from the centre of the cylinder toward its other end, which is covered with a plastic lid. With the cup in this working position, a beam of gamma-rays is emitted by the thulium plate perpendicular to the end face of the apparatus.

When the unit is not being used, the cup holding the source is automatically returned inside the passage. The gamma-rays being emitted by the source do not penetrate to the outside because, owing



to the curvature of the passage, they are absorbed by the lead.

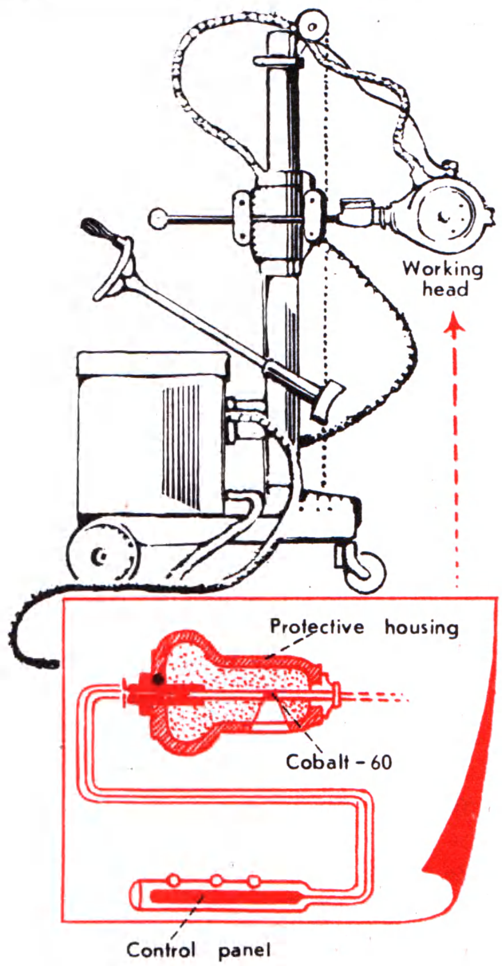
The whole unit weighs about 2,5 kilograms. It is safe to operate, and is suitable both for medical purposes (radiographic examination and treatment), and as an industrial defectoscope, since the radioactive radiation of thulium can penetrate steel 2.5 centimetres thick.

Determining the thickness of items. The light and dark patches seen on X-ray photographs of the human body or of some object indicate that some parts allow X-rays or gamma-rays to pass while others stop the penetrating rays to a varying extent. The general rule here is that the denser, i.e. the heavier, the substance put in the path of the rays, the more intensely it blocks them. Hence, it follows that an X-ray plate or photograph can serve at the same time as a measure of the density of the substance examined. By comparing the lightest and darkest spots of the image with a previously measured standard specimen, it is possible to determine the thickness of the item irradiated.

In gamma-units specially designed for this purpose, film is replaced by an instrument that measures the intensity of the gamma-rays reaching it, e.g. an ionization counter.

The variation of an electric current can be used to control the machine producing the material. When, for instance, the

Pocket-size gamma-unit with a thulium-170 source



An external view and diagram of the working head of an industrial gamma-ray unit used to inspect thick ingots and steel plates

thickness of the material becomes less than that required, the current brings a special mechanism into action that immediately increases the gap between the rolls of the machine so that the thickness of the rolled sheet or strip is increased. Its thickness can be reduced in a similar way.

Radioactivity and the chemical industry. Polymerization is the name given in the chemistry of organic substances (mainly in the chemistry of artificial plastics) to reactions in which a large number of molecules combine in a long chain, forming a gigantic molecule, known as a polymer. Radioactive radiation sometimes facilitates initiation of polymerization that is very difficult or impossible to induce by other means.

When exposed to radiation, some plastics acquire quite unusual properties. Thus, for instance, polyethylene, a plastic widely used for parts in the radio and electrical engineering in which higher insulating properties are required, considerably increases its dielectric strength at high temperatures after exposure to gamma-rays.

Wood, impregnated with certain plastics and irradiated with very hard (short-wave) gamma-rays, is turned into a new material seven times as strong as the original wood, which is, in addition, easily glued, and resists warping.

The sole method of producing petrol used to be distillation of petroleum at high temperatures and pressures. But now, it has been found that acetylene bombarded with high-energy beta-particles polymerises into petrol with a minimum yield in the initial experiments of 20 per cent. The process can be conducted at a temperature no higher than 25°C.

As we already know gamma-rays are very short electromagnetic rays or, to put it simply, invisible light, each photon of which possesses very high energy, and consequently is more capable of doing work than a photon of visible light.

Now the chemical process by which certain substances known as halogens (fluorine, chlorine, bromine, iodine) combine with other chemical elements is hampered by the fact that it develops very slowly in the dark and that to speed it up sources of bright light are needed. Hitherto many of these processes have been speeded up by means of ultraviolet lamps. But gamma-rays, that are many times more active than ultra-violet rays, make it possible to raise the rate of many of these processes.

A vast number of chemical reactions are based on processes of oxidation, the most important of which are chain reactions in the presence of oxygen. But many of them develop too slowly, or are very difficult to regulate as desired.

In recent years scientists have run into phenomena that are still not fully solved. When a rocket fuel like propane, for example, before entering the combustion chamber is passed through a fine strainer (with apertures 0.001 cm in diameter) made of gold wire irradiated in a reactor to a total radioactivity of the order of 10 000 curies, the combustion efficiency of the fuel is 50 per cent higher than ordinary.

'Labelled' Atoms

Let us suppose that you need for some reason to identify who goes to the theatre, to sports stadiums, amusement park and libraries.

In a crowd you recognize soldiers quite easily by their uniforms, schoolchildren by their school uniforms and age, and so on. It is easier still to sort out a mass of soldiers. Their military ranks can be determined from their badges

of rank, and their branch of the service by the appropriate badges, and uniform.

In practice, engineers and scientists and production workers come across similar problems. It is often necessary to determine the behaviour and location of substances that are invisible to the eye, for example, the way in which two, apparently similar liquids, or two invisible gases are distributed in a mixture; where impurities of some sort are located in a bar of metal; where a medicine given to a person or animal goes, and how rapidly, and so on. It is impossible to distinguish all these differences by the unaided eye, and more or less complicated indirect methods are needed.

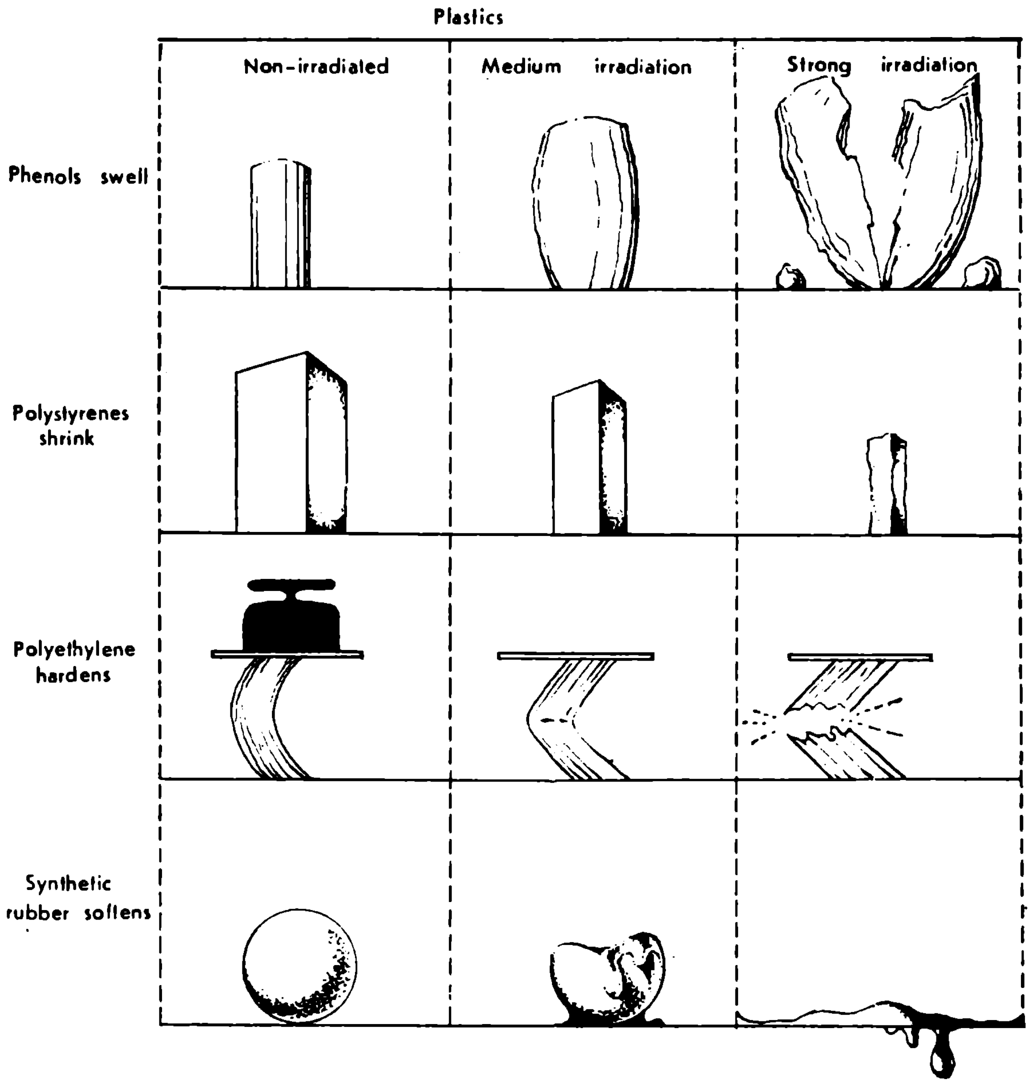
The problem, however, becomes particularly involved, and is often quite insoluble, when the measurements must be made in motion. Say it is necessary to investigate the flow of a river: where it is fast, where slow, where even, where turbulent, where compressed, as it were, where expanded, etc. Water must be labelled to do so. Investigators pour various dyes into it, glass balls or corks, or at night a great many little boats with candles are launched, and the investigated section is watched from a high bank. But what is to be done when the process to be investigated is more complicated and inaccessible?

The great Russian chemist A. M. Butlerov dreamed in his day of finding a substance that would let us penetrate into the molecules of the most complex substances like proteins, high-molecular carbon compounds, etc., in order to 'see' how their atoms were arranged and in what order, how they moved and where and when they entered into chemical reactions.

Now, of course, there are instruments available that make indirect counting possible, and even observation of individual molecules and atoms, but we have to learn how to follow their continuous variations and transformations in motion and at rest, in solids and in gases, in liquids, in living organisms, and in cells, which is much more difficult than simply detecting them or even counting them.

In short, scientists were very much in need of methods in the world of atoms and molecules like those used to study the routes and nesting places of migratory birds, the movements of fish and bees and other creatures, in other words, to label or mark them. The fisherman who catches a labelled fish, or the hunter killing a ringed bird, posts the tag or ring found to the scientific organization concerned. Thus the place where the fish or bird had been tagged is marked on a special map, and where and in what circumstances it was caught or shot. A lot of returned tags or rings make it possible for scientists not only to draw to various conclusions, but also to predict things about the future.

The discovery of radioactivity made it possible to realize the scientists' dream. The atoms of radioactive substances proved to be very 'noisy'. No matter where they were, in what directions they move, in what chemical reactions they took part, they made so much 'noise' continuously emitting nuclei or particles or gamma-rays, that they could be traced by means of quite simple instruments. An ionization counter counts the individual particles flying through it, a Wilson cloud chamber or photographic emulsion enables their tracks to be observed, without any need to introduce foreign, alien atoms into the investigated substance, atoms that would disturb the development of a physical or chemical process to some extent. The investigation can be carried out using only radioactive isotopes of the substance being studied.



Substances like plastics can be given quite unexpected properties by exposing them to radioactivity

Thus, for example, a certain amount of radioactive iron is introduced into a mass of ordinary molten iron, and the way it spreads through the melt is studied. This immediately shows how the iron mixes during melting, depending on the temperature. On the other hand, one can introduce a certain amount of another radioactive substance into the molten iron, and then use the casting to investigate where molecules or atoms of the admixture accumulated. It is very convenient, because the radioactive atoms emit continuously signals: 'Here I am', 'There is such and such a number of us here'.

The ease with which radioactive isotopes or labelled atoms can be introduced into any substance, whether a chemical compound, mixture, complex organic compound, or living organism, and then detected in them made it possible very rapidly to devise new methods of investigation, applicable literally in all branches of science, technology and industry.

Let us look at several examples.

Imagine that a small but dangerous crack that can cause serious trouble has formed in a water main or gas main buried deep under a busy street. It is very difficult, almost impossible, to locate the crack exactly. What is to be done? Dig up the whole length of the main for several kilometres? Or wait for a bigger, more easily detectable leak?

But, if we introduce a small, safe quantity of a radioactive isotope with a short half-life into the water or gas flowing through this main, then a little later, at the point where the leak is, enough of the radioactive atoms will penetrate into the ground around 'yelling' their presence there. They can be comparatively easily detected by a counter, fixed to the end of a special probe and inserted into the ground all along the route of the main. The damaged spot will be detected at once. Or the signals reaching a counter carried along the route on a van can be recorded on magnetic tape or wire of a length corresponding to that of the main. Then when the tape is played back on a tape-recorder in the laboratory, the recorded signals of the radioactive emissions can be reproduced through a loudspeaker. As soon as a terrific din is heard, the tape is stopped, its length is measured, and an emergency crew are sent to the spot where trouble has been detected.

Signalling atoms that indicate their location in a substance and all stages of their movement and transformation are a very valuable means of control, observation, and investigation, and they shall have a great and brilliant future in science, technology, and industry.

But these are the simplest, the elementary, so to say, ways of using 'labelled' atoms, the primary school of 'small scale' atomic power. They can be made more complicated, and made active instead of passive. Active methods have found very wide application in chemistry, biology, and medicine. Let us look at some of them.

Isotopes in Biology

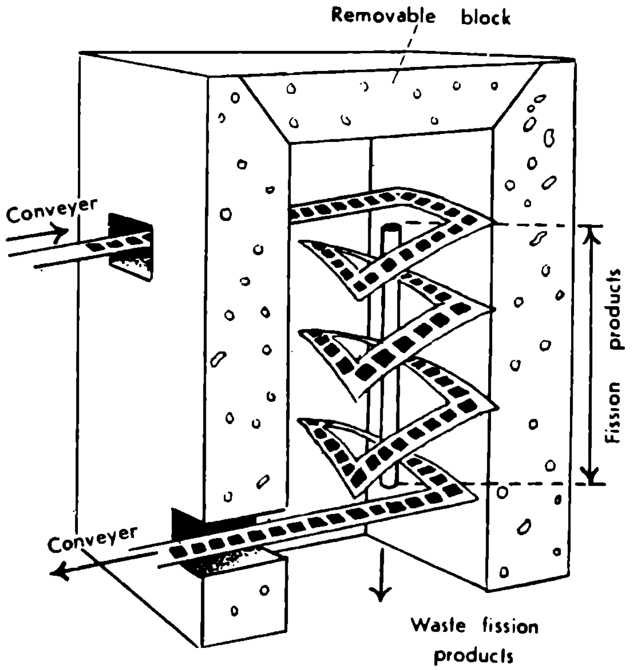
From the time X-rays found wide application in biological research it has been known that light irradiation has a very favourable effect on living organisms, speeding up growth, development, reproduction, etc. But, more intense irradiation first depresses the organism, and when increased, has a destructive effect on it and can even kill it.

For a long time the most reliable way of sterilizing various substances, i.e. of killing all kinds of bacteria was to heat them to a comparatively high temperatures of 100°C or above.

But many substances, especially perishable goods, undergo such serious chemical alterations and changes of flavour when heated that high temperatures sometimes cannot be used.

The fact that living organisms first break down when exposed to ionizing radiation, and then perish, suggested using 'cold' sterilization.

Indeed, all the living organisms present in most ordinary foodstuffs can be completely killed by a flux of beta-particles, and even better by gamma-rays directly in the packaging (cellophane, cardboard boxes, glass jars, and tin cans). Such sterilization after packag-



Conveyer for cold sterilization of drugs

ing prevents their becoming contaminated during irradiation.

It is particularly convenient to irradiate products on a conveyer. On coming into the active zone of a powerful radiation source, microbes are either killed or rendered sterile, so that their further multiplication and development ceases.

Radioactive sources are also used to sterilize plant pests, for instance, to protect grain from that most harmful pest, the weevil.

The value of the technique is that it does not require such big doses of radiation as complete extermination (100 to 1 000 times weaker), which is most important when products are irradiated on a conveyer, or very large quantities are to be treated in a comparatively short time.

Simple, effective, cheap but powerful means of sterilization are particularly useful in medicine to ensure absolutely reliable decontamination of medicines, pharmaceutical preparations and other medical goods which must often be completely sterile from the moment of preparation to the moment of use.

The sprouting of potatoes during long-term storage gives much trouble to people in the vegetable business and public catering. No matter what measures are taken, and what storage conditions are observed, a time comes when the potatoes begin to sprout with the result that a great part of them rot and become unusable just at the most important time of the year, depriving consumers of a valuable food and wasting transport and storage facilities.

Irradiation of potatoes by gamma-rays makes it possible to postpone the sprouting period for 18 months without loss of their nutritional properties; that gives a practical solution to the storage problem.

Not content with what had been accomplished by means of such passive ways of employing radioactivity in biology, scientists gingerly proceeded further, conducting tests aimed in particular at increasing yields and creating new sorts of crop. As a result of gamma-radiation, for example, a new sort of oats has been evolved immune to certain fungal diseases, and a barley with a yield exceeding that of ordinary barley by 5-6 per cent, etc.

By irradiating seeds before sowing with small doses of gamma-rays, it is possible, in favourable climatic conditions to ensure earlier blooming and more rapid development of plants; sometimes seeds are soaked in a radioactive solution before sowing for the same purpose.

Direct irradiation of certain plants by strictly dosed radioactive isotopes accelerates their development and ripening. This is a circumstance of great importance in a country like the USSR for extending the northern limit of

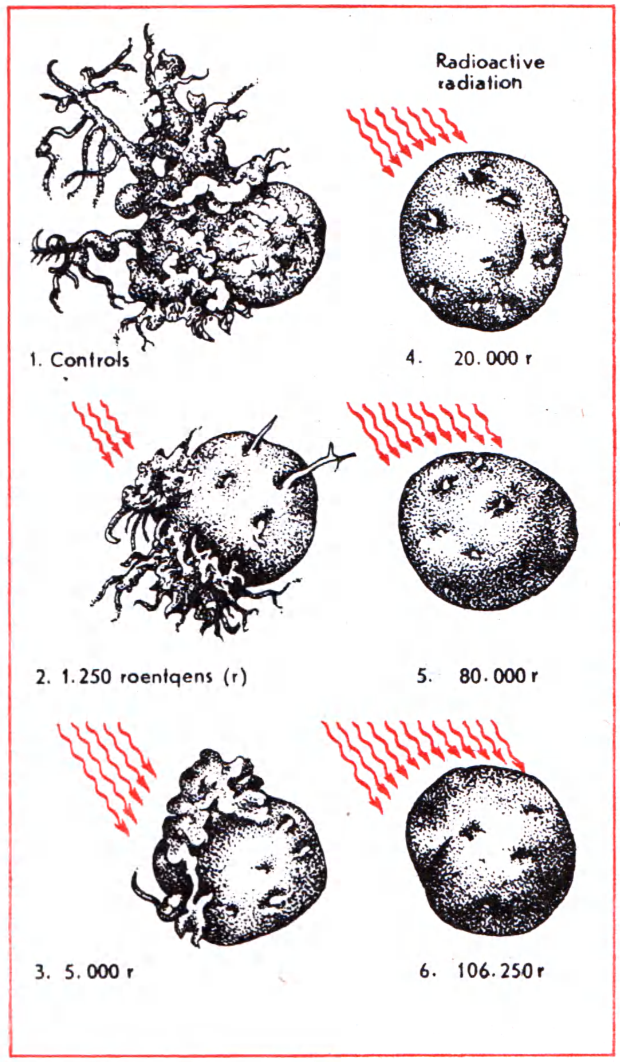
southern crops to areas where the summer is very short and many crops consequently simply do not have time to ripen.

'Labelled' atoms are of great help to scientists in investigating the very fine and delicate physiological functions of plants and living organisms, in particular, in studying metabolism, for example, how plants assimilate fertilizers placed in the soil at different depths and at various seasons. They have also been of help in discovering the method of top dressing plants by spraying them with nutrients, which can even be done from an aircraft. (It used to be thought, incidentally, that nutrients should only be placed into the soil, at the roots of the plants.)

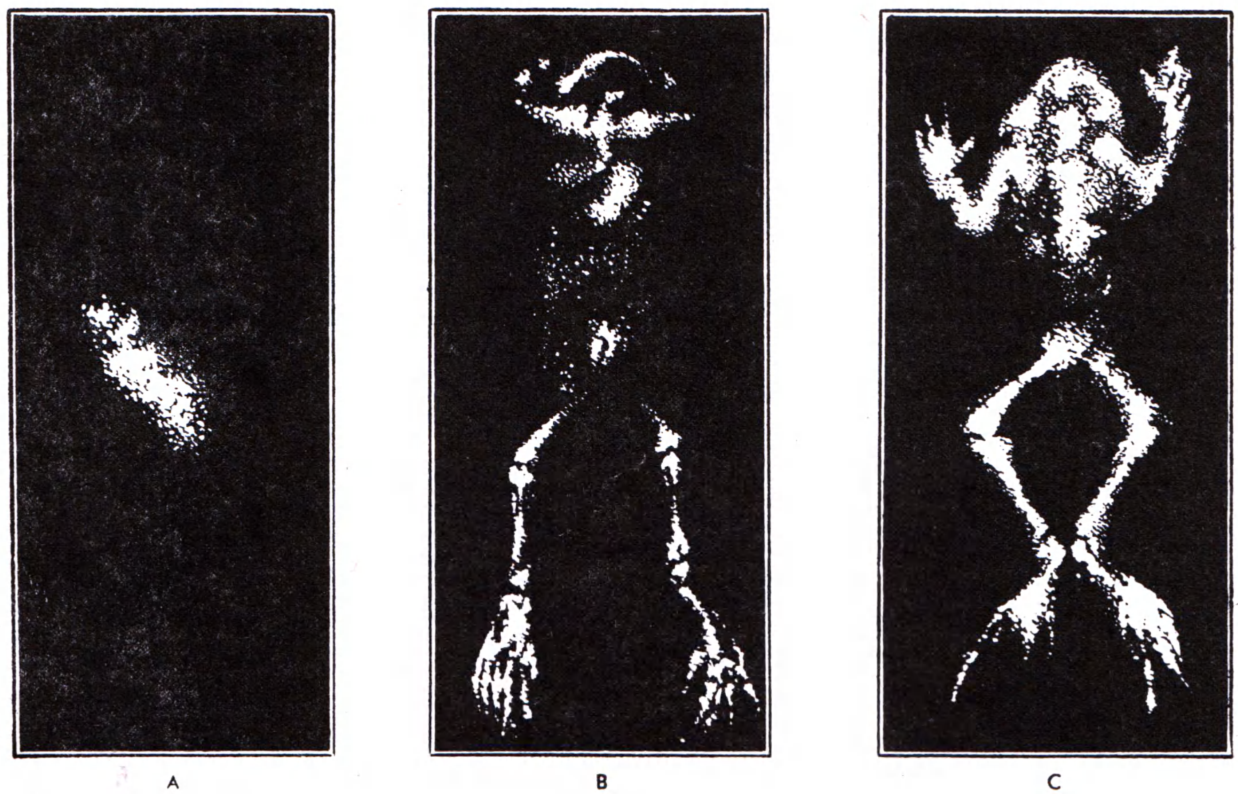
Isotopes in Medicine

Drawing on their long and extensive experience of using radium and rays to investigate and treat the living human organism, scientists began using radioactive substances, introducing them into the organism with proper care and sometimes, we would say, with a certain restraint.

In justification of their care, the famous case should be recalled when women workers in a watch factory, painting hands and dials with a luminous compound, put the tip of the brush into their mouths, so as to moisten it. The luminous paint, however, contained a tiny quantity of radium, the emission of which made the ingredients of the paint luminescent. Since the human organism retains a number of the substances that enter it, including radium, even the infinitesimal quantities of this element entering the organisms of these workers proved sufficient for its continuous radiation to begin to disrupt their blood-forming organs and the women affected died.



Irradiation with gamma-rays prevents the sprouting of potatoes



Autoradiograph of a frog after injection of radioactive phosphorus into its blood: *A*—after 20 minutes; *B*—after 48 minutes; *C*—after seven days

But the possibility of producing artificial isotopes with the most diverse half-lives and energy radically changed all habitual ideas and previously existing misgivings on the subject. It has long been known, for instance, that the young, very rapidly multiplying cells of a cancerous tumour, are destroyed sooner when exposed to X-rays than the surrounding and more slowly multiplying healthy cells. And successful treatment of cancer was based on that. But it is only effective in dealing with external forms of this dreadful disease, such as cancers of the skin, mucous membranes, etc.

The healthy tissue surrounding a tumour hampers the penetration of gamma-rays to the internal organs for a sufficiently long time, so that fewer rays reach the growing malignant cells than the healthy tissue.

Radioactive isotopes opened up a way to attack the sick organ, in accordance with the old saying that a fortress yields easiest from the inside.

It had previously been found that several of the internal organs of man and animals concentrate certain chemical elements that enter the organism in various ways. Iodine, for example, accumulates mainly in the thyroid gland, phosphorus, in the bones, manganese, in the liver, and so on. From the isotopes produced by uranium fission or prepared artificially in a nuclear reactor, it is possible to choose isotopes of a sufficiently short half-life that are selectively absorbed by a diseased organ.

A short time after these isotopes are introduced into the organism the bulk

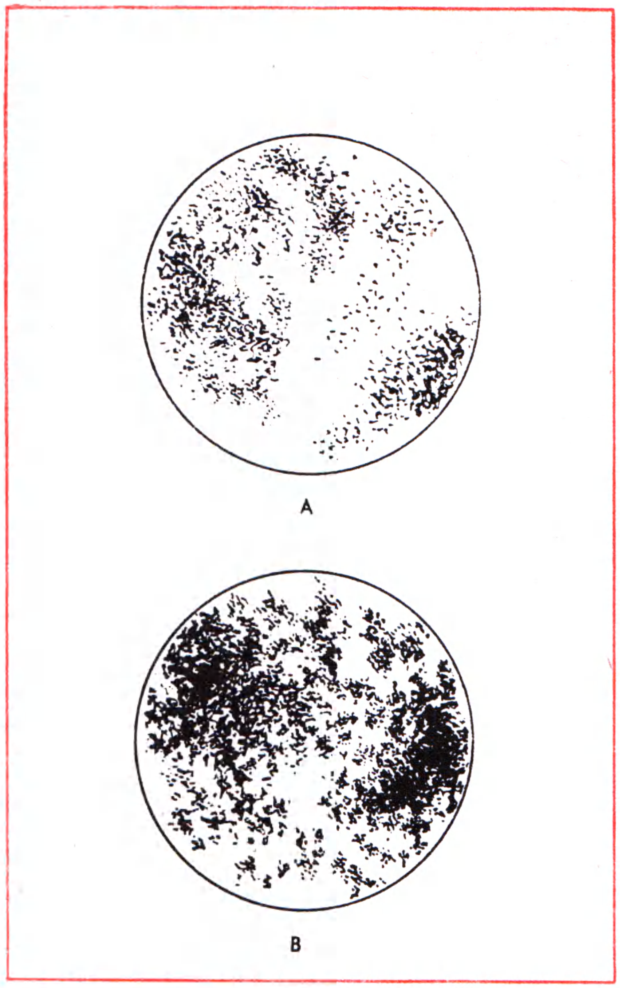
of the isotope is accumulated in the organ affected by the malignant tumour.

In this case the radiation emitted by the radioactive isotopes is directed from the inside to the outside, and the rays do not have to make their way through the thick, sound tissue. They first encounter the malignant tissue destroying it before sound cells begin to suffer. If the half-life is carefully calculated, and the appropriate isotope selected, the latter should have disintegrated fully by the time its useful effect is over. Cancers of the thyroid gland and of the blood-forming organs are now treated in this way.

Sometimes doctors must proceed in another way, introducing either a tiny ampoule or a liquid (colloid) solution of a radioactive substance that does not react with human tissue into organs that are not able to accumulate definite elements. Decaying at a high rate, these substances irradiate the diseased section, and after the radiation ceases they remain in the organism doing no harm to it.

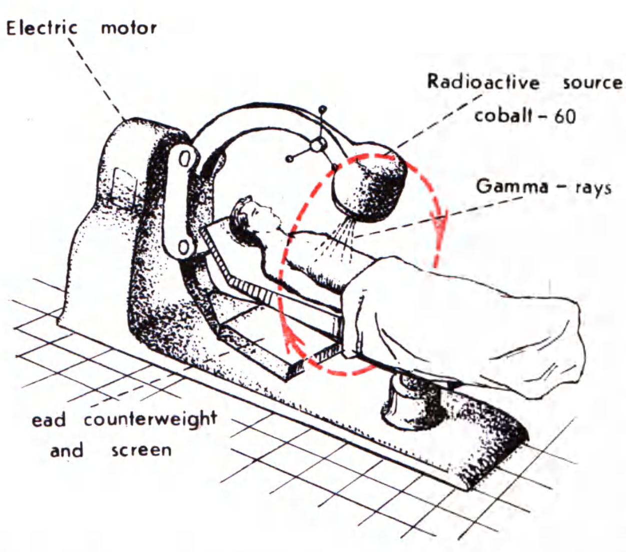
Our picture overleaf shows a radioactive gun that can be used to shoot a tiny particle of a radioactive substance (gold) into a diseased organ to a preset depth. The microscopic particle hurts less than the prick of the finest needle, and the small wound begins to heal at once. The little radioactive shell begins its destructive work on the malignant tumour and after a definite time becomes a harmless piece of metal.

Doctors place great hope on the radioactive isotopes of substances that accumulate in various parts of the organism but are dissolved comparatively rapidly and removed from it. These substances include sodium, tantalum, and other elements. They may prove helpful where either the whole organ or some part of it must be exposed to weak radiation (e.g. the blood, liver, gastro-intestinal tract, lungs, brain, etc.).



(*A*) In normal conditions the thyroid gland absorbs a comparatively small quantity of radioactive iodine; but when affected by cancer (*B*) it begins to accumulate very much

Radioactive substances can sometimes be 'shot' into a diseased organ



To avoid needless damage to adjacent organs, the cobalt gun can be rotated around a patient

When such substances are introduced into the organism and reach the diseased organ, the latter is exposed to neutron bombardment. Absorbing neutrons, the substance becomes radioactive for a short time, and irradiates the diseased organ or area. Three times more boron accumulates in a malignant tumour of the brain, for example, than in ordinary brain cells.

When a small quantity of sodium borate is injected into the blood of a patient, and the malignant section of the brain is irradiated in a short time with slow neutrons from a nuclear reactor specially designed for the purpose, the nucleus of boron-10 on capturing a slow neutron becomes excited and ejects an alpha-particle that strongly ionizes and rapidly destroys only brain cells containing boron. The radiation acts for so short a time that no harm is done to healthy cells containing a smaller quantity (one-third as much) of boron.

Radioactive isotopes are thus actively used in the struggle for human life.

Radiation Hazards

What is the effect of any kind of radiation on a substance? What can be considered a high, a medium, and low level of radiation? What in fact is meant by radiation? How is it determined? And how is it measured?

Beta-particles. The effect of charged particles on any substance is based in the first place on the effect of the ionization that occurs when a high-velocity and high-energy particle, e.g. an electron (beta-particle) knocks another electron out of an atom of the irradiated substance, thereby creating a positively charged atom (positive ion) and a free electron (negative ion), i.e. a pair of ions. The unit of radiation intensity is the roentgen, which is equal to that quantity of radiation that produces ions of

both signs equal to one electrostatic unit each in one cubic centimetre of air at normal atmospheric pressure of 760 mm Hg and °C. One roentgen forms in 1 cm of dry air 2.08×10^9 ions of either sign, which is the same as the number of ion-pairs.

As may be seen from the Table on page 187 the most important and convenient fission products, emitting only beta-particles, are strontium-90, yttrium-91, technecium-99, and promethium-147.

These isotopes can be produced in the purest form, so that the hazard of their containing admixtures, capable of emitting gamma-rays, can be avoided, and there is, therefore, no need for the containers with very thick protective walls that are used to store gamma-ray sources.

Since beta-particles have a low penetrating capacity, they do not require thick shielding, and protection can be ensured by means of a fairly thin envelope. But there is one rather unexpected hazard. Abrupt deceleration of high-velocity electrons directed at some dense substance (metal) causes the appearance of X-rays of high penetrating power, known as braking X-radiation.

The penetrating power of this X-radiation increases with electron velocity and with the density (atomic weight) of the substance involved. So, to weaken this very objectionable secondary radiation, the protective envelope surrounding the radioactive isotope emitting only beta-particles needs to be two-layered, viz. an inner layer, made of a substance of a very low atomic weight, plastic for example, to arrest the beta-particles, and an outer layer, of a substance with a high atomic weight (like lead), to absorb any X-rays developing.

Gamma-rays. The most valuable property of gamma-rays is their ability to penetrate all substances occurring in nature to great depth.

Unlike beta-particles, gamma-rays, being electromagnetic waves of an extremely short wavelength, cannot be retained in any definite layer of a substance. They can only be weakened or attenuated.

Gamma-rays are also able to ionize the atoms of the substance through which they pass.

Because radioactive radiation, be it a flux of particles or gamma-rays, ionizes the atoms of substances encountered on its path, it is extremely harmful and dangerous to men and living organisms even in very small doses. It is particularly hazardous for the health of future generations, since its harmful effects can be inherited.

From their very birth men are exposed to the continuous action of radiation of all kinds. Cosmic rays pierce them. The rocks and soil around them contain microscopic quantities of radioactive substances that are permanent emitters and these substances are also present in food, and water, and the air.

Since the beginning of the twentieth century new hazards to mankind have been added to these inevitable and unavoidable ones, hazards created by man himself. The 'permissible' dose of all the types of radioactive radiation that (in the opinion of Soviet scientists) a young person may receive during the first thirty years of his or her life without appreciable danger to future generations amounts to ten roentgen units (*r*); only 3.1 of it comes from cosmic radiation and from the radioactive radiation given off by the natural environment, to which men have become adapted to some extent in the course of thousands of years of evolution.

In medical practice X-rays are now widely used to examine the lungs, stomach, teeth, and other internal organs. In 30 years these seemingly innocent and harmless irradiations add an average of another three roentgens.

A thing as trivial as a wrist watch with a luminous dial, whose production involves a tiny quantity of radioactive substances, adds up to 0.5 *r* when worn regularly, which is quite an appreciable fraction of the total of ten units.

The total comes to 8-10 *r*, i.e. to almost the entire, not so harmless 'permissible dose' and it is possible that some people may receive a quantity exceeding that. In this connection the testing of atomic weapons presents tremendous danger. If tests are not stopped completely, future generations will be exposed to considerably higher levels of radiation.

Radiation in large doses at one time is a direct and undoubted danger to animals and men. A dose of 600-800 *r* is lethal to man, although various organisms resist it in a different way. A guinea-pig is killed by 300 *r*, dogs by 600 *r*, rabbits by 1 250 *r*. Radiation of 350 *r* kills only 10 per cent of rats, but many withstand up to 700 *r*. There are bacteria that support a radiation dose 10 000 times greater than the dose considered lethal for man.

It is also important whether an organism is irradiated all at once or gradually with large doses or small ones. Thus a guinea-pig exposed daily to a radiation of 4-5 *r* dies only after it has received 2 900-3 000 roentgen units.

Wherever people have to work with radiation sources (reactors, accelerators, X-ray units) very careful precautions are taken to protect them and to check exposure. Thanks to these measures, radiation sickness if and when it occurs, is the result either of very rare accidents, or of downright carelessness.

In all dangerous places the quantity of radiation received by personnel is strictly checked and recorded. For that purpose instruments are used that automatically monitor the level of radiation in premises when people work. In the event of the level of radiation rising for some reason or other, an alarm signal warns all personnel to leave the premises immediately. In addition, each worker carries an individual monitoring instrument that makes it possible at the end of the day to determine the total dose of radiation he or she has received. If the dose received by workers exceeds the permissible level, they are laid from work for a certain time.

A Clock That Measures Millenia

The possibilities of using 'low' atomic power for the good of mankind are really inexhaustible. It is a great pity that we had to restrict ourselves to only a few examples illustrating its use in modern science and engineering.

To show how widely radioactive isotopes are now used, we cannot resist telling you in conclusion about one more very fascinating example.

If the parent substances of the three series of radioactive elements, uranium, thorium and actinium, had a comparatively short half-life, it is quite obvious that they would long ago have ceased to exist on Earth, and we would not even have suspected today that ordinary, common lead had such notable ancestors. And it may be that other radioactive elements occurred on Earth in remote times, whose descending chains have completely decayed, and that many of the stable and inoffensive elements well known to us happen to be their less fortunate descendants. Who knows!

But we do know exactly now that the half-life of U-235 is 710 million years, of U-238 4 500 million years, and of thorium even as much as 13 900 million years. Consequently, they have existed for a very long time, since the depths of time.

And the more exactly the scientists succeed in determining the total life of

some radioactive element or other, the more frequently use is made of these far not silent witnesses, which count out their own specific time in the course of thousands of millions of years without ever running fast or slow, to determine the age of rocks and geological formations.

Wherever scientists discover uranium, they also find its breakdown products. It has been calculated that 0.000137 of a gram of lead accumulates in one gram of natural uranium in a million years. So if we carefully measure the amounts of uranium and lead we can determine the time when a given mineral was formed with great accuracy.

This method also makes it possible to determine the age of rocks by the proportions of uranium-235 and lead-207, of thorium-232 and lead-208, and finally of lead-206 and lead-207.

The age of the Earth can be determined more accurately by means of the potassium-argon method. Natural potassium consists of two stable isotopes, K-39 (93.08 per cent) and K-41 (6.91 per cent), and it also contains an unstable isotope, K-40 (0.01 per cent). Potassium is very abundant in nature, and is a constituent of the most important rock-forming minerals. It is also noted for the very high stability of its isotopic composition.

Radioactive K-40 disintegrates in two ways: 88 per cent of its atoms undergo beta-decay, forming the stable calcium isotope Ca-40, while the other 12 per cent turn into an unstable isotope of argon, A-40, which, after emitting a gamma quantum, turns into the principal, stable isotope of argon, A-40. The half-life of K-40 is 1.30×10^9 years. The decay of K-40 gradually leads to its reduction in the natural element, and to the accumulation of decay products, A-40 and Ca-40. By measuring and comparing the quantities of these isotopes left, it is possible to determine the absolute age of rocks.

But only geologists, geophysicists, astronomers and a few other scientists count time in thousands of millions of years. Most other scientists are interested in the exact determination of shorter periods of time, counting not in millions of years, but in hundreds of thousands, or sometimes just thousands, of years. For that they must resort to quite another method, of cosmic origin, that of using radioactive carbon-14.

Where does this comparatively rare isotope of carbon, seldom occurring on Earth, come from?

Since the time it was formed, our planet has been subjected to continuous bombardment by cosmic rays, particles possessing tremendous energy, measured in tens and hundreds of thousands of million electron-volts. These cosmic particles split nuclei encountered in the atmosphere, knocking out neutrons and other fragments. The stray neutrons in turn are captured by atoms of nitrogen-14 and a nuclear reaction takes place, resulting in the formation of an atom of radioactive carbon-14, and the ejection of an atom of hydrogen (proton). The half-life of this carbon is about 6 000 years.

Carbon is one of the most active elements in nature. Once formed, it is 'attacked', for example, by oxygen atoms and, combining with them, forms carbon dioxide (dioxide of carbon-14). The omnipresent wind and the mutual diffusion of gases thoroughly mix the molecules of this continuously formed 'labelled' gas with those of ordinary carbon dioxide.

Everything then follows its usual course; carbon dioxide is absorbed by plants, and animals and people eat the plants as food, together with the radioactive carbon in them.

And that simple circumstance, in fact, is the principle behind the method of measuring, or dating, by means of radioactive carbon-14.

Somewhere, sometimes an animal fell sick, stopped eating, and died. Five thousand years later a palaeontologist discovered one of its bones during excavations. He made certain measurements, and determined when the fossil animal lived.

How did he manage it?

The radioactive carbon-14 accumulated in the body of the animal began to disappear after it died. Its atomic nuclei disintegrate at a certain rate, and half of the original amount accumulated will disappear in 5 568 years, half of the remaining amount in another 5 568 years, so that only an eighth of the original quantity will be left after 18 000 years, and so on.

So, by determining the residual radioactivity of the bone, the scientist could determine the time the animal died.

But what quantity of radioactivity did he assume as the original amount? The answer to that illustrates the refinement and accuracy of this method. The point is that the amount of its radioactive isotope in ordinary carbon has not changed for millions of years, because there is a natural balance between the newly formed and decaying atoms of carbon. Consequently, the amount of radioactive carbon that should be taken as the initial amount is equal to its percentage in the natural carbon occurring in nature around us.

Having established the initial amount for our unusual clock it only remains to determine the difference between the radioactivity of carbon-14 in the living matter around us, and that of the C-14 detected in the fossils of animals or plants that lived and died several thousand years ago.

Any animal or plant living today contains the same quantity of carbon-14 per gram of weight as an animal that died 5 000 years ago, namely, about 50 000 million atoms. But the number of atoms of C-14 in the bones of the excavated animal has now fallen by half. If only a quarter of the initial radioactive atoms remained, we could say that the animal lived and died 10 000 years ago, and so on. Simple, isn't it?

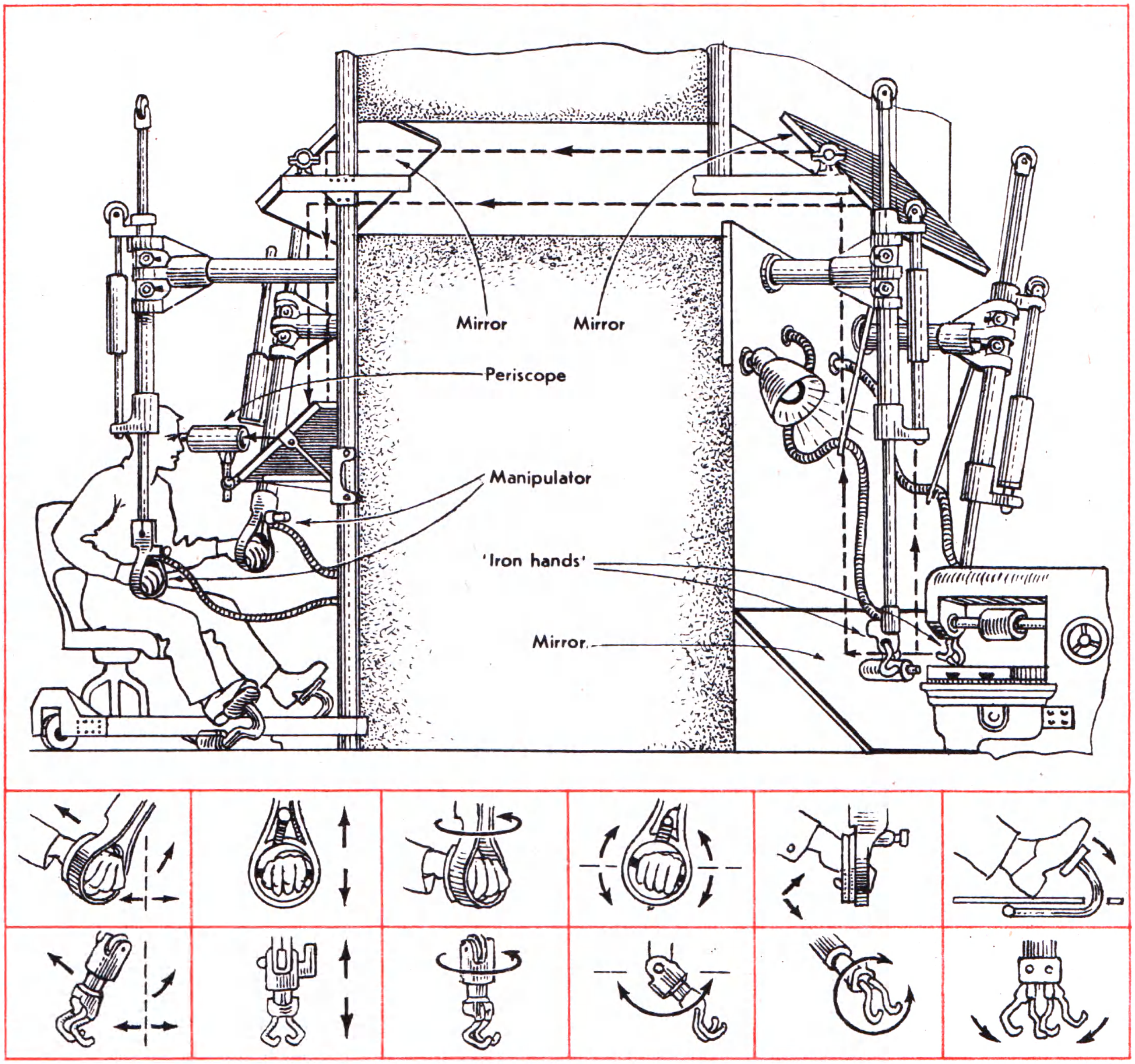
The method was checked using samples of tissue from Egyptian mummies, the date of whose interment was known exactly. The results proved its correctness.

The method gives reliable results within a range of 20 000 years. But as more and more sensitive apparatus is built for identifying the presence of atoms of radioactive isotopes in fossils it will be possible to extend that period. For the fact is that after 60 000 years, a time equal to ten half-lives of C-14, only 0.1 per cent of the radioactive isotope remains; and at present it is still difficult to detect the radiation of that amount in samples and to measure it accurately.

Before we go on to our next chapter on the future of atomic energy, we must just touch on a very interesting field of engineering concerned with radioactive isotopes.

'Hot Labs' and 'Iron Hands'

The isotope of any element irradiated in a nuclear reactor is radioactive and so 'hot' that for some seconds, minutes, even hours it may at first be equivalent to tens or hundreds of kilograms of pure radium as regards the number and intensity of the particles and gamma-rays emitted by it. So long as it is kept behind the reliable concrete walls of the reactor, there is no problem of how to handle it. But as soon as it is delivered in a special container to the place where it is to be employed dozens of problems



arise at once. How to use it? How to handle it? And so on.

It is impossible, of course, to carry out research with such materials by conventional techniques. It was therefore necessary to build special 'hot' laboratories where investigations could be made with them without any danger to the people involved.

The laboratory is usually housed in a special building with a number of caves

'Iron hands' (manipulators) are indispensable in hot laboratories

or cells connected by a long corridor suitable for interlaboratory transport. All the laboratory premises are separated from one another by thick concrete walls impenetrable to any radiation. And the doors between them are made of layers and layers of steel plates with interlayers that absorb dangerous radiation.

In such laboratories they study either the properties of all the different isotopes irradiated in nuclear reactors, or the ways in which they affect other substances. So the laboratory must have ways and means available for processing the substances obtained, for conducting mechanical, physical, and chemical investigations, and for making many intricate measurements. It all must be done from a distance, from behind reliable shielding, by means of complicated automatic and remote controlled mechanical devices, including television sets.

One of the caves is the machine shop to which the isotopes are delivered in lumps, packed in thick-walled lead boxes (or containers) and brought along a special access road. Here they are extracted from the containers by means of automatic devices. Then samples of the required shape and size are made from the isotopes on milling machines and other machine tools.

The samples to be investigated are stored in an adjacent cave. Further along the corridor are caves for metallographic and physical studies, and mechanical testing.

The samples are transferred from cave into cave, and from instrument to instrument by means of a transporter wagon that moves along the corridor, guided from the control rooms of the 'hot' caves concerned.

In caves where not so 'hot'—'semi-hot'—samples are treated and tested, the operators observe the samples through viewing windows made of special thick lead glass that reliably protects them against radiation. The interiors of 'hot' caves are lined with stainless steel plates that are easily washed and cleansed of radioactive contamination. Each cave and operator's room and all auxiliary rooms are fitted with special instruments permitting the level of radioactivity in them to be monitored and controlled.

All operations are carried out from the operator's room by means of a manipulator, a very interesting instrument that is a kind of extension of the operator's hands through the thick shielding and directly inside the 'hot' cave. By means of it the scientist experimenting with radioactive substances is able accurately and faultlessly to execute the most complicated movements normally performed by the human hand, while standing behind the thick shield protecting him against dangerous high-intensity radiation.

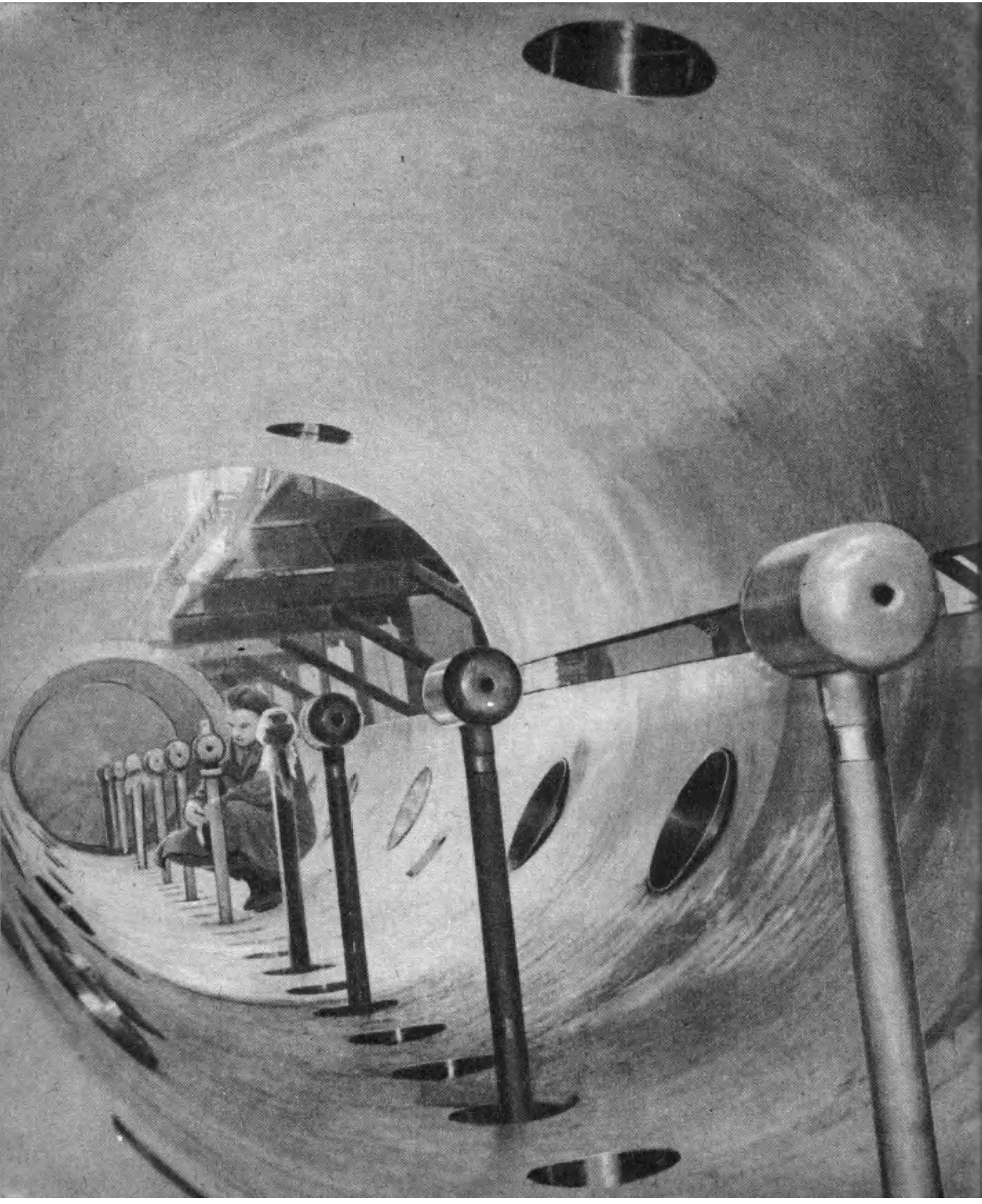
In the years since nuclear reactors first appeared the 'iron hand' has undergone interesting developments and improvements. At first all kinds of overhead cranes, levels, and automatic devices were used as manipulators, but in spite of all improvements to them it remained difficult to work them. The movements of the contrivances were awkward and clumsy until they began to be given the shape and movement characteristic of the human hand and fingers. Manipulators that copy the natural movements of the experimenter can be used to execute movements that are at times even difficult for the human hand, as well as for rough work and transfers within the 'hot' cave.

The accuracy of their movements is amazing.

One can peel a hard-boiled egg with a manipulator, for example, without damaging the white, or to tie a knot in a thick strip of iron. Manipulators can be used to weigh samples on an analyti-

cal laboratory balance, to measure a part with a micrometer, to slacken a screw or nut, etc.

Operators observe the performed work through a periscope, a system of mirrors arranged in a special curved channel built in the thick concrete wall. But where necessary, instruments in a cave can be read by means of binoculars, a microscope, or a television set.



Chapter Twelve

THE FUTURE OF ATOMIC POWER

Blazing a New Trail

It would be a great mistake to think that our present achievements in the release and use of atomic energy are the end of the long path that people took many many years ago.

For the enormous quantities of energy released by men in the nuclear fission reaction of uranium amounts to only 0.1 per cent of the energy contained in the atomic nucleus. The non-controllable thermonuclear reaction makes it possible to increase the quantity of energy released slightly.

And how much energy does man need?

Lots and more than lots. And not simply energy, but energy in its most concentrated form, atomic energy.

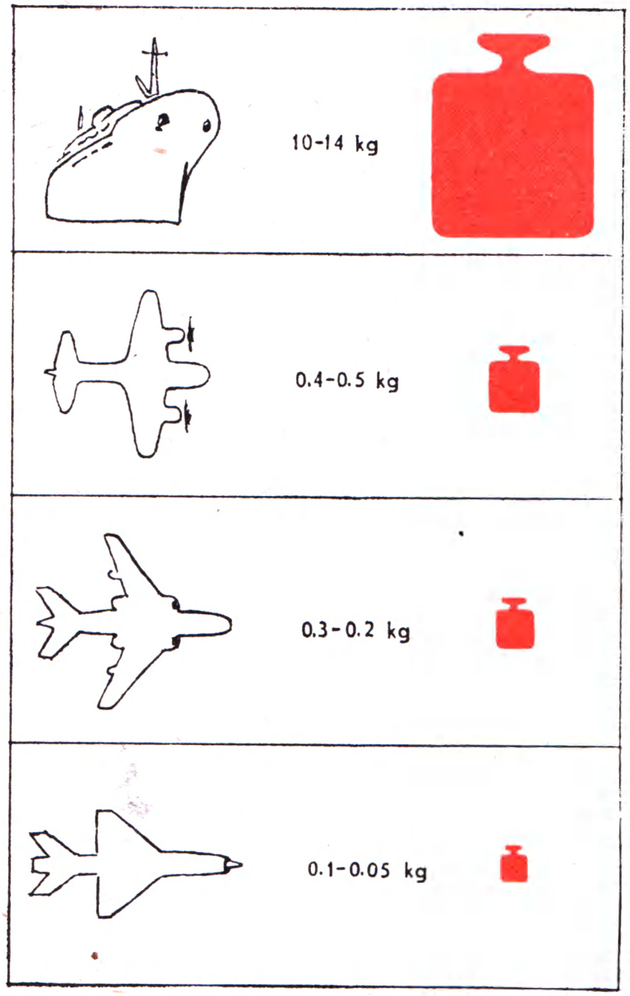
It is still difficult now to say how all this will happen exactly, but the general features of the way to the solution of some problems can already be envisaged. Let us look at the most important of them.

On Engines in General

Man has long pinned his most precious hopes on a new source of energy of unlimited power, of infinitely small size and boundless duration, but consuming almost no fuel at all. Even when he still had no such unusual source of power, he was not content to fly among the eagles. He wanted to fly to the stars!

Well, this marvellous source of almost unlimited energy and power is in our hands at last.

Any new engine for propelling ships, motor cars, lorries, trains, or aircraft must have a number of advantages over all other previously used. It should be more powerful, lighter, simpler, use less fuel, be simpler to make and use, and be stronger and more reliable in operation.



The weight of engines per horsepower

Let us begin with power. The most compact engines, as regards power developed, are aircraft engines. Ordinary piston engines, with dozens of working cylinders to generate 3 000-4 000 horsepower can be built but with great difficulty. Modern jet engines develop a thrust corresponding, in aircraft flying at top speed, to 35 000-40 000 horsepower and higher. And short-duration rocket engines develop a thrust corresponding to millions of horsepower.

A nuclear reactor consuming about one kilogram of fissionable uranium a day develops thermal power of the order of one million kilowatts (one thousand megawatts). Used as source of power in an electricity generating station of 35 per cent efficiency it will yield 350 megawatts of the most convenient form of energy for use, electricity. This amount of power is sufficient to propel the largest ship, the most powerful locomotive, or the largest aircraft.

But theoretically the power of an atomic generating station is not limited by these figures. It can be doubled by burning up two kilograms of nuclear fuel a day, or quadrupled by burning up four kilograms.

A second, very important aspect of an engine is its weight. The lighter an engine of a certain horsepower rating is, the wider its field of application will be. Leaving aside the special conditions of the operation of an engine, its degree of perfection is usually determined by its weight per horsepower.

The weight per horsepower of heavy stationary engines intended for reliable continuous service, in thermal power stations, for example, or in ships, is between 10 and 14 kilograms.

An aviation piston engine, intended for comparatively short-time operation at maximum power, weighs around 0.5-0.4 kilogram per horsepower; a turbojet engine weighs 0.3 to 0.2 kilogram per horsepower, a thermal jet engine 0.10-0.05 kg per horsepower, and a liquid fuel rocket engine 0.010-0.001 kg per horsepower.

And an atomic installation? Alas, it is too high compared with its competitors. But the weight per unit power is not the most vital index.

Any form of transport is designed for a certain number of operating hours without refuelling a ship, for example, for months, a locomotive for a day, an airplane for tens of hours, and a jet aircraft for hours.

So, no matter how improved and light an engine is, one must not simply take

its weight into account but its weight and that of the fuel needed for continuous operation between refuellings. That changes things considerably. For instance, the engine propelling a 10 000 ton ship may weigh, say, 1 000 tons, but for a voyage it is also necessary to take on board 2 000-3 000 tons of coal or oil. Consequently, the weight of the ship's power plant plus the fuel must be reckoned as 3 000-4 000 tons.

In addition, no ship can be worked for a whole navigation season or on a very long voyage without refuelling. That usually makes it necessary to have a separate fleet carrying coal and oil to various ports, which is often a complicated and costly business, irrational and occasionally impossible. All that also should be added in an indirect way to the 'weight' of a ship's power plant.

An aircraft flying 8 000-10 000 kilometres in 12 hours, and whose engines weigh two or three tons, must take on 10-15 tons of fuel, and sometimes even more. It is said, not without reason, that modern heavy aircraft are flying fuel tanks. An airplane weighs, say, ten tons, its engines two or three tons, and the fuel 10-15 tons, while the useful payload is only a few tons. In other words, a modern aircraft carries more of itself, than people or cargo. And the weight of it per horsepower engine is not as small as it would seem at first, when we did not take into account the heavy ball and chain of the fuel tanks attached to it.

After that long introduction, we can now talk about atomic power plants.

Is it profitable to use an atomic reactor as a source of power for various engines?

At first glance, it does not seem feasible.

Its weight per horsepower is not 0.5, 1.0, or even 10 kilograms. The concrete shielding of the smallest reactor known must weigh at least 300-500 tons, irrespective of its power.

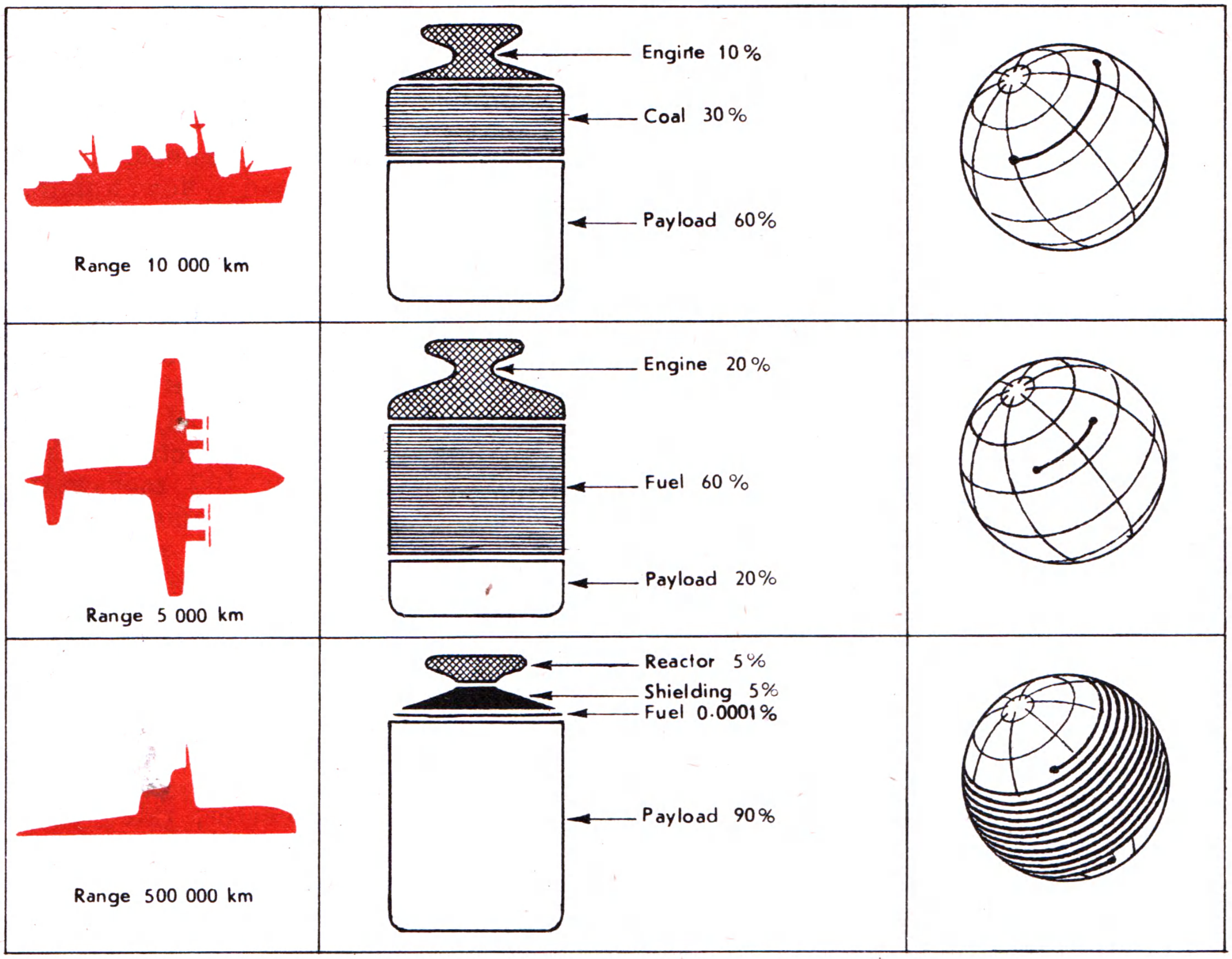
And the most annoying thing is that the weight of the reactor itself, including the uranium fuel, moderator, neutron reflector, and cooling system is not so very great. Types are known, whose weight does not exceed a few hundred kilograms.

But against its disadvantages, when we consider the whole weight of the plant, including the store of fuel carried, a nuclear reactor has undoubted advantages. We recalled above that an atomic power station of the order of 100 megawatts, incorporating a reactor with a thermal power of 300-400 megawatts, consumes only 500-600 grams of U-235 or plutonium a day, which amounts to about 0.2 tons a year. But in plants incorporating a regenerative or breeder-type reactor, a fraction of the fuel can be recovered or a larger amount of fuel produced.

Imagine now that a ship of 10 000-12 000 ton displacement is powered by a thermal nuclear reactor, rated at 40 or 50 megawatts. The reactor weighs about 1 000 tons, the nuclear fuel to be carried on the ship about half a ton, the turbines 1 000 tons and all the other equipment another 600 tons. The total weight of the installation is 2 600 tons, compared with the 5 000 or 6 000 tons of an ordinary ship, including its fuel bunkers.

While an ordinary ship with full bunkers cannot cover more than 10 000 kilometres, a nuclear powered ship can sail for anything from 300 000 to 500 000 kilometres without refuelling.

To cover such a distance a ship with ordinary propelling engines would need to take on fuel about 35 times, carry 80 000 to 90 000 tons of unnecessary load in its hull, and require the services of a whole fleet of coal vessels or tankers to carry the fuel, and an army of people, a whole system of bases and ports, and so on.



It is more correct to calculate the specific power and weight of an engine, including the weight of the fuel consumed in a certain period of time

From what we have said we can conclude that with all the foreseeable improvements in atomic plant in the near and more distant future, nuclear reactors will probably only be used as propelling agents for a long time in large and heavy ships and submarines, and perhaps in colossal transport aircraft.

And the motorists and motocyclists, and writers of science fiction, who dream of motor ways and highways in the near future, and of city streets filled with atomic cars and motorbikes, and the air with private airplanes powered by nuclear engines, it seems, will have to wait a long time.

The First Atomic Ice-Breaker—The 'Lenin'

An atomic installation proved very suitable for an ice-breaker. Very large ships of this type are powered with steam or diesel engines of from 10 000 to 25 000 horsepower.

In the summer of 1960, the world's first atomic ice-breaker, the 'Lenin', made its maiden voyage. It's displacement was 16 000 tons, and its engines gave 44 000 shaft horsepower, which was two to two and a half that of the biggest ice-breakers in the world.

The advantages of the 'Lenin' over other ice-breakers powered by any other kind of power plant are enormous, and sometimes incomparable.

First and foremost is its constant displacement and consequently constant and optimum ice-breaking qualities, for there is no need in carrying large stores of diesel oil or other fuel or, as fuel is consumed, to replace it with an equal amount of water ballast, to transport which a good half of the fuel carried and of the power developed is consumed.

The fact that it practically does not need to refuel makes it possible for a nuclear-powered ice-breaker to make voyages of any length and duration, and to operate at full power without fear of being left without fuel and becoming iced up in places where no other ice-breaker can get to it.

The exceptional capabilities of the atomic plant of the 'Lenin' can be judged from the fact that its reactors worked without refuelling for three years (1960-62) and it could still go on without replacing its nuclear fuel for another navigation season. With an economic operation of its reactors the ice-breaker 'Lenin' could sail around the world eight or ten times without refuelling.

Speaking generally atomic marine engines make it possible to build ships that can sail at speeds double those of any present-day vessels. The ice-breaker 'Lenin', however, has other duties, so its cruising speed is comparatively low; it makes 18 knots in clear water, and two knots when breaking its way through ice 2.4 metres thick.

Ice-breakers of the old type have to spend a considerable part of the short precious time when navigation is possible in waiting for an improvement in ice conditions. They can open passages for ships in ice up to 70 to 90 centimetres thick, and with an ice nip of two points they are unable to offer any help to ships.

But in such conditions an atomic ice-breaker fully preserves its manoeuvreability and freedom of action. The ice-breaker 'Lenin' has made it possible to double the length of the Arctic navigation season. The dream of S.O. Makarov, the great Russian admiral and creator of the Russian ice-breaker fleet, is coming true: 'To break through to the Pole'.

In designing the reactor for the 'Lenin' special attention was paid, other problems apart, to the strength, reliability, and safety of the unit. The sailing of any ship, even in open waters very often entails great difficulties and hazards. We only need recall that the striking force of a sea wave as high as a six-storey building may sometimes be as much as 35 or 40 tons per square metre of the hull surface of a ship. But an ice-breaker, in addition to being able to withstand that shock, must be able to ram and break ice two metres thick, striking the same block several times at full speed.

Obviously such operating conditions are not to be compared with those of conventional stationary power plants. At the same time the nuclear reactor must be protected against pitching and rolling, against quick rises and falls, and particularly against vibration.

The crew of the 'Lenin' works and lives throughout the whole navigation season not more than 50 to 100 metres from the source of dangerous radiation. Therefore the safety requirements of the ordinary and emergency shielding of the reactor must be far more stringent than those imposed on land-based power stations. In short, absolute protection must be provided, as if the ice-breaker were powered by ordinary fuel and not by nuclear energy.

In view not only of these requirements, but also of other very important considerations it was decided to power the ice-breaker with a water-cooled, pressu-

rized-water reactor, with the water serving, in addition, as a neutron moderator. That made it possible to design the core of comparatively small size thereby reducing the total weight of the biological shielding considerably, or rather making it more effective.

The ice-breaker could be powered with only one reactor of the heat power required, and that would have made it possible to cut down the total weight and volume of the entire power plant, but after all pros and cons had been carefully and thoroughly weighed it was decided to install three reactors, with one of them normally in reserve and to be brought into operation whenever there was any trouble with the main reactors service or in the event of specially difficult ice conditions.

The cylindrical steel vessel of each reactor is five metres high and two metres in diameter, and is lined with stainless steel to ensure protection against corrosion.

The core is 1.6 metres high and one metre in diameter. The fuel used is uranium dioxide, containing up to 5 per cent of the fissionable isotope, U-235. The total weight of fuel charged in a single reactor is 1.7 tons, so that the total weight of the fuel in the three reactors is 5.1 tons, of which about 250 kilograms is U-235.

It must be remembered that the heat power or capacity of a reactor is four or five times greater than the electrical power of the generation plant. The heat capacity of each of the Lenin's reactors is 90 megawatts, and the total of all three 270 megawatts. Water delivered to them at a pressure of 200 atmospheres is heated to a temperature of 325°C.

Since any impurities dissolved in the water become more radioactive than it does, the water circulating in the primary circuit is double distilled.

As in the usual arrangement, the water removing heat from the core of a reactor is passed to a tubular heat exchanger or steam generator, where it gives up its heat to the water of the secondary circuit, converting it into steam at a temperature of 310°C and a pressure of 28 atmospheres.

This steam is used to drive the four main steam turbines of the ice-breaker, each of which drives two direct current generators, working at 1 200 volts. One of the two generators has a capacity of 3 840 kW; the other actually consists of two generators in a common frame, each rated at 1 920 kW.

The three screw-propellers of the 'Lenin' are driven by three electric motors, a central one rated 19 600 horsepower, and the two side motors of 9 800 horsepower each.

Such a system provides for very flexible control and manoeuvreability, and ensures reliable operation of the entire power system.

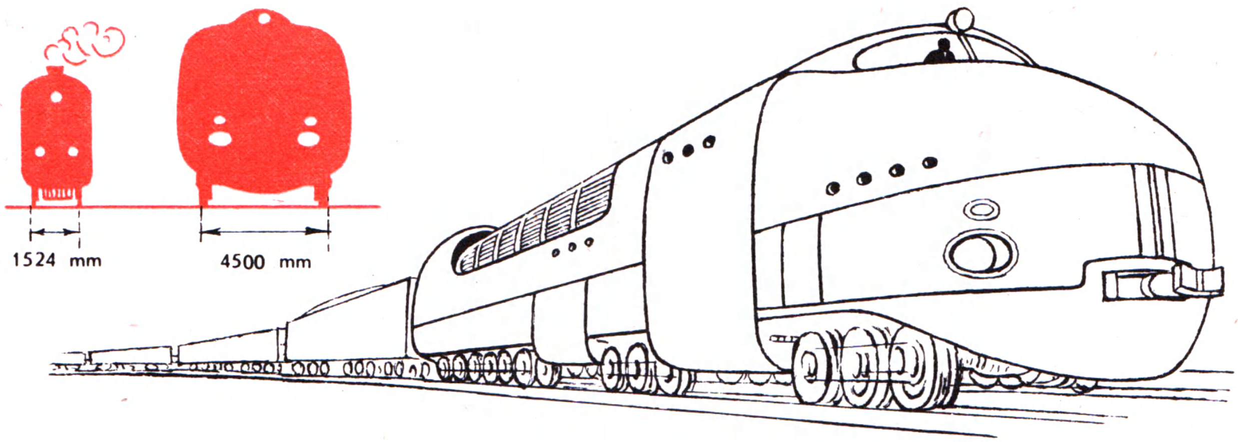
The higher power of the central propulsion motor is based on the fact that the propeller turned by it is better protected against damage than the others, and is in fact the main propeller.

The fact that the propellers are driven by electric motors and not directly from the steam turbines makes it possible to vary the speed of the ice-breaker within wide limits; it is easier to control it directly from the bridge and not by means of engine-room telegraph as on ordinary ships.

In addition to the main turbogenerators there are two auxiliary ones, each rated at 1 000 kW, supplying current to all the ship's mechanisms.

The power plant of the ice-breaker is put into operation by means of a stand-by diesel-generator set rated at 1 000 kW; there are also two diesel-generator sets serving as stand-by capacity for the two auxiliary turbogenerators.

All the components of the primary



Atomic locomotive and train of the future

circuit of each reactor are surrounded by biological shielding consisting of several layers of water and steel. This shielding comprises water-filled tanks in which steel plates are immersed. Some of the equipment of the primary circuit also serves as supplementary protection.

The equipment of the primary circuit in which radioactive water circulates is protected by steel walls 300-400 millimetres thick, and in places of complex shape by concrete to which limonite ore is added.

The level of radioactivity on board is controlled by means of two monitoring systems, one technological, the other biological, ensuring full safety for the crew.

Atomic Locomotives

Our picture illustrates how the writer and illustrator envisage the appearance of an atomic locomotive and a double-decker broad gauge (4.5 m) train of the future. It is possible, even probable, that it will not be as we depicted, but the drawing is not so far, perhaps, from the truth.

What circumstances must be taken into account in designing atomic locomotives?

Unlike sea-lanes, railways run through populated areas, consequently a reactor mounted on a locomotive must be fully protected on all sides, at the bottom, and also at the top. And that means, above all, that for a reactor to be suitable it must combine such features as small size and maximum possible power.

Furthermore, however strict and thorough the safety measures taken to ensure safe traffic and train service, nevertheless one out of many locomotives could have an accident somewhere.

The locomotive then must be so designed that the radioactive substances in the reactor core, in the heat-removal system, and the coolant circulating between the reactor and steam turbine do not escape in the event of an accident.

That problem inevitably leads to the need to design a very intricate power plant.

Let us consider one of the projects for an atomic power plant for a conventional locomotive.

You will remember that the smallest reactor of the types now known and seemingly possible is the homogeneous 'boiling water' reactor working on enriched uranium, usually a uranium salt dissolved in heavy water. Such a reactor is designed as a metal sphere not more

than 30 centimetres in diameter, built of stainless steel.

With 9 kg of pure U-235 in its solution (or soup), this reactor is capable of developing about 30 000 kilowatts of heat and with the whole thing operating with an efficiency around 20-25 per cent, the effective power of the locomotive will be between 5 000 and 7 500 horsepower.

A nuclear reactor of this type consuming about 25-30 g of U-235 a day is capable of operating continuously for several months without refuelling.

The locomotive must be so designed that after it has covered a certain distance it would be possible to withdraw the metal sphere filled with the soup of the reactor and replace it with a new one.

The small volume of the core of homogeneous reactors allows it to be designed and suspended in such a way that should there be an accident the 'soup' will not escape into the outer sections of the reactor.

The inevitable jolting and bumping involved of railways, which are unlikely to be eliminated for the locomotives of the future, make it very difficult to create absolutely reliable connections between pipes and other components and to isolate them from air and water in the event of the slightest accident. Therefore, no matter how tempting it might be to think of cooling the reactor with liquid metal, such cooling system could not be made suitable.

Only the simplest, most reliable, and cheapest solution is left, that is, to use ordinary water pumped under pressure into the reactor as the heat-removal agent, or some organic coolant.

For the same reasons there is no need of a heat exchanger. The inevitable loss of heat in it would reduce the already not very high efficiency of the locomotive. The steam turbine must therefore be operated with the high pressure steam generated directly in the reactor. But that is quite possible. The main drawback is the high radioactivity of the steam, which will contaminate not only the turbine and condenser, but also the apparatus and devices through which steam and water flow.

The volume of the material required for biological shielding will then be not less than 150 cubic metres and weigh around 500 or 600 tons. Concrete can be replaced by other materials, like iron or lead.

If lead is used the useful space of the power unit, guarded by lead walls, can be made quite big, permitting free arrangement of the equipment and convenient access for maintenance and control.

The electrical generator supplying current to the many electric motors driving the wheels of the locomotive does not require concrete shielding.

The total length of the atomic power plant and auxiliary equipment is estimated around 50 metres.

Atomic Aircraft

People have been dreaming of flying from time immemorial. Here is a real field for atomic energy—to fly faster than sound for as long as one wants, above the clouds, to fly to remote, seemingly inaccessible planets, and to other stellar worlds!

The power generated by a huge modern hydroelectric station, like the Volga, Bratsk or Krasnoyarsk dams, would be more than enough to launch a very large earth satellite or an interplanetary spaceship. But it is impossible to use even the 'smallest' hydroelectric station as the power unit of a spacecraft, or gather together and concentrate the power generated by it, so as to load it into an aircraft, rocket, or spaceship. And it is

difficult to imagine, let alone expect that we will succeed in the near future in developing means of transmitting enormous quantities of power by a directed radio beam, without transmission lines.

The ideal example of enormous energy densely packed in a small volume is the nuclear reactor.

In principle a reactor, mounted on an aircraft flying at high altitude, could do without a cumbrous and heavy biological shielding, except on the wall facing the passenger and service compartments. The shielding could then be made much smaller, since radioactive radiation needs only to be arrested within the limits of a narrow cone.

But while stationary on earth, the reactor must be shielded on all sides.

And how can these seemingly contradictory requirements be met?

There are several different ways. The atomic unit, for example, can be placed either in the rear or front section of the fuselage, or at the ends of the wings, so that, on landing, the reactor would be put into special compartments or 'boxes' the walls of which (2.0-2.5 m thick) would ensure normal biological shielding.

The weight of the protective shield isolating the passengers and cargo from the reactor can be reduced in a number of ways. The fuselage, for instance, can be made so long that the passenger cabin is a score of metres away from the reactor, and, the 'shadow' of a shield of minimum thickness would cover a maximum area.

Then, the engines or turbines themselves could be between the cabins and cargo holds and the reactor, and serve to a great extent as shielding, if materials and metals are used in their design that do not fail rapidly when exposed to radiation.

Additional protection could be provided by placing water tanks and luggage holds between the atomic unit and passenger compartments, storing loads insensitive to radiation there, and also the compartment accommodating the undercarriage and so on.

The remaining space can be left without protection in flight provided other aeroplanes are kept at a distance of several hundred metres from the atomic aircraft.

What would the engines of such an aircraft be like? The jet or reaction-propulsion engine is now considered the most perfect. It enables thermal energy to be converted into motion with no intermediate stages such as connecting rods, crankshafts, and other devices that reduce the efficiency of an engine. (The characteristics and specifications of existing types of jet engines are given in the table below.)

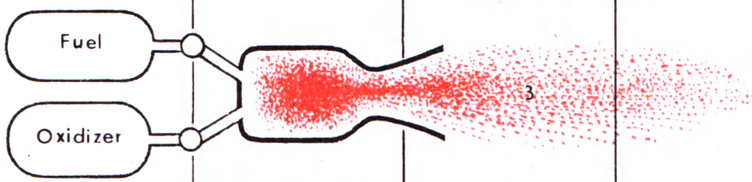
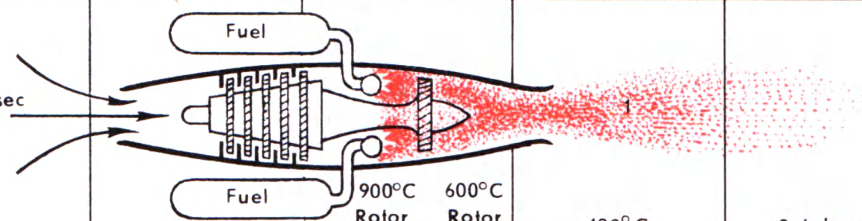
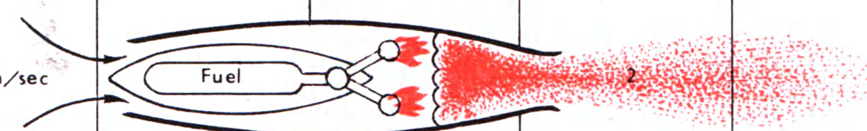
Only 30 per cent of the oxygen fed into the combustion chamber and of the heat potential of the high-energy fuel is consumed, because of the insufficient heat resistance of the materials from which combustion chambers, turbine blades, and other parts of jet engines are made.

If materials able to withstand temperatures above 2 000°C for a long time were available, the speed of present-day jet aircraft could be doubled. So the further development of jet-propelled aviation very much depends on whether better heat-resisting materials are developed in the next few years.

If a nuclear reactor replaced the combustion chamber of a jet engine, it would also replace present-day fuel of any kind, since the temperature of air blown through the reactor could be raised above 800° to 1 000°C.

Several possible schemes for atomic engines are shown on p. 219. Their design is almost the same as that of conventional jet engines.

Air entering the unit passes through

Air intake velocity	Type of engine	Combustion temperature	Exhaust gas temperature	Exhaust gas velocity	Relative fuel consuption, kg/h per kg thrust
	 Rocket	up to 3 000° C	up to 2 000° C	2.28 km/sec	15
250 m/sec	 Turbojet	900°C Rotor inlet; 600°C Rotor outlet	400° C	0.6 km/sec	1
600 m/sec	 Ram jet	2 000° C	1200 °C	1.2 km/sec	3

Modern types of jet propulsion engines

the reactor (which may be either fast-neutron reactor or slow-neutron reactor with a graphite moderator) through a large number of metal-lined channels. Metal of high heat capacity is used for the channels and the core of the reactor is of elongated shape, which enables the stream of air to be more easily heated to the temperature required. The hot air is directed through the compressor turbine and is then ejected into the atmosphere through the exhaust nozzle.

In turbojet engines air is drawn in by a compressor and passed, after heating, to the gas turbine. A ram jet engine is of simpler design; air directly enters the combustion chamber via the inlet port and hot air is expelled so eliminating any need for a compressor and turbine. But this type of engine can only operate at very high speeds.

Owing to the enormous power generated by an atomic unit the degree to which air entering the heating chamber is compressed could be raised to a level that is impossible in ordinary jet engines, and the air is readily heated to a very high temperature. High compression of a large volume of heated air gives a big increase in engine power and in the velocity of the jet of air escaping through the exhaust nozzle into the atmosphere, which in turn increases the speed of the aircraft.

But now let us consider another type of engine, whose future very likely depends on nuclear reactors, that is to say, an engine suitable for a spaceship.

Interplanetary Spaceships of the Future

Many years ago the great Russian scientist Tsiolkovsky worked out a way for man to make a voyage into interplanetary space on a rocket ship. The only engines that could have been used then to attempt such an extraordinary flight were the pyrotechnical rockets or fireworks fired on holidays and festive occasions.

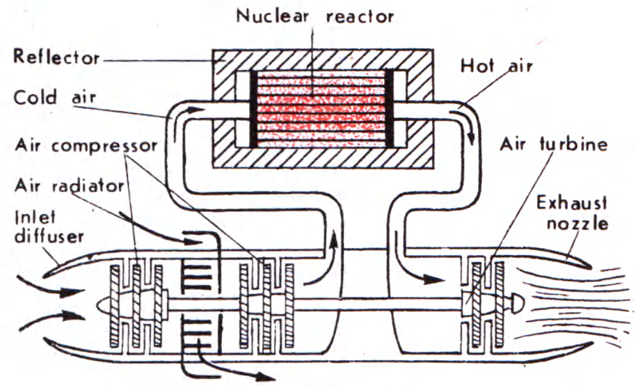
It was as far a cry from firework rockets to a spaceship as from uranium paint to a nuclear reactor.

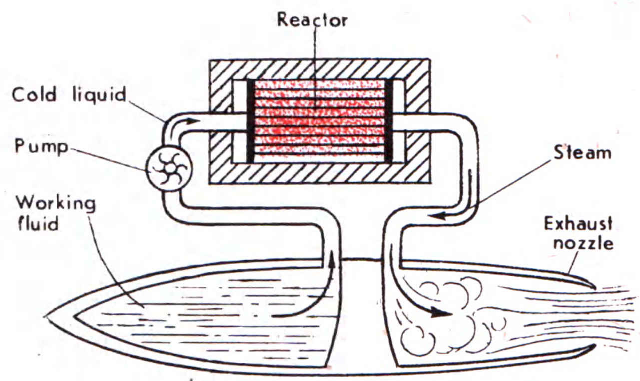
But the small noisy firework, pouring out a long tail of fire and smoke during its flight, was the tiny model of its future big brother.

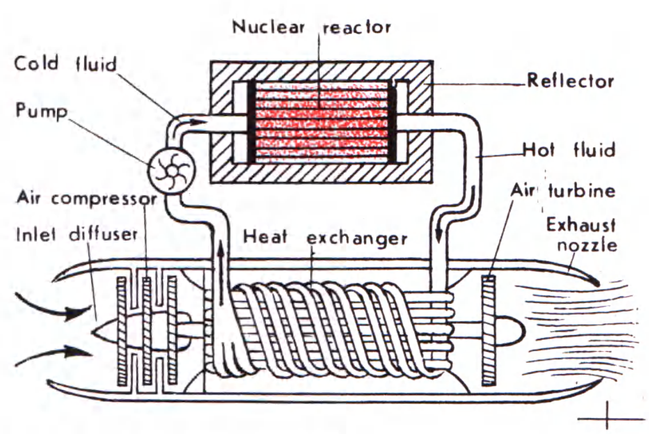
For a space rocket to break the strong clutch of Earth's gravity it must attain a speed around 11.2 kilometres a second. The best types of fuel available in Tsiolkovsky's time only gave a speed a tenth of that. It was sad to think that space flights would only be something for people of the Twenty-first Century.

In the years that followed, however, the speed of rockets was greatly increased through the use of new kinds of fuel.

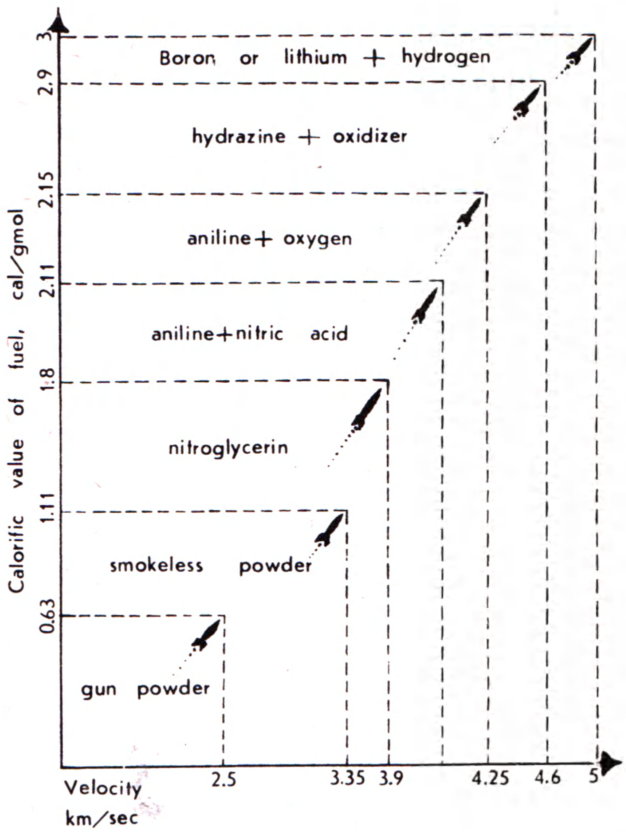
And even in the unfavourable conditions of imperfect grades of contemporary heat-resistant alloys these new grades of fuel already make it possible to attain the desired 11.2 km/sec. But this speed need only be developed for a few minutes, just sufficient to leave the sphere of Earth's gravity; then, obeying the laws of celestial mechanics, the rocket can travel in free flight to land on some planet or other. All that need be done in addition would be to correct its trajectory by means of small auxiliary jet engines that would not require large stocks of fuel. That exactly, in

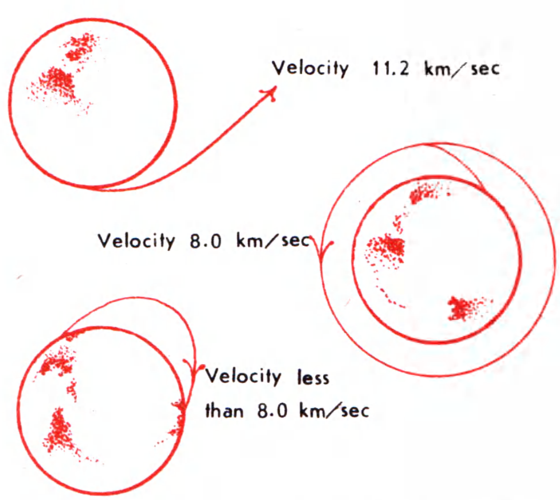






Possible designs of nuclear engines for aircraft





Calorific value of fuels used in rockets, and the velocities developed by them

fact, is how the flights of Soviet and American rockets to the Moon, around the Moon, to Mars and to Venus have been accomplished.

In actual space flight, whether manned or unmanned, the rocket must have sufficient stores of energy, and hence of fuel, so that its engines could run not just for a few minutes but for months or years. For a spaceship must be able to reduce its launching speed in order to land on the planet required to take off from it, and, on returning to Earth, once again to reduce for landing. Roughly speaking, it takes about as much fuel to decelerate a rocket and land, as to launch it and accelerate it to the required escape velocity.

To take off from the Moon for a return flight to Earth, a considerably lower second cosmic, or escape, velocity is needed as to launch a rocket from Earth, namely 2.7 km/sec instead of 11.2 km/sec, and so a rather smaller amount of fuel is required. On the other hand, much more fuel would be required to launch a rocket from the surface of Jupiter or Uranus than from the Earth. That is why designers pin so much hope on the nuclear reactor.

Inventors will have to overcome superhuman difficulties, but no one doubts that the space rockets of the future will need atomic engines.

A nuclear reactor of the future, free of its main drawbacks, and above all of the excessive weight of the biological shielding and protective envelopes, when installed in a space rocket will undoubtedly be the most perfect source of energy for its jet engines, making it possible to produce practically any power for a very long time. The limit here, as we have already said, would be the quantity of heat that could be continuously removed from the reactor, the temperature the various components of the reactor and engine could withstand, and the

weight of the uranium charge and of the material that will be heated in the reactor to maximum temperature and be expelled through the exhaust nozzles.

Unfortunately, both the quantity of heat removed from the reactor and the heat resistance of the materials that will be available in the near future and for some time to come do not permit us to make optimistic forecasts.

At present the materials from which the combustion chambers, tail pipes, and other components of rockets are made can withstand maximum temperatures up to 1 200°C, but it is safe to say that materials will be available in 20 or 30 years time that will withstand temperatures not exceeding 3 000° to 4 000°C. But that is very far from the temperatures of thirty, fifty and one hundred thousand degrees that engineers will be needed for really long flights in stellar ships.

It takes several days for a rocket to reach the Moon. Taking into account the need for maximum fuel economy and taking advantage of the most favourable launching and escape conditions a flight to Mars even of a nuclear-propelled rocket takes at least 250 days, and a flight to Venus 150 days. In flights to other worlds time will have to be counted in decades, centuries, and millenia, periods beyond the powers of a single generation of people.

Ion Engine

In reaction propulsion engines and rockets thrust is created by very hot gases, products of the combustion of chemical fuel, flowing from them with great velocity. The amount of thrust mainly depends on the mass of the exhausted material and the exhaust velocity. In ordinary engines working on chemical fuels the exhaust velocity of the wastes gases does not exceed 3 000 to 5 000 metres a second. Consequently the only way to increase the thrust developed by jet engines of any type is to increase the mass of the combustion products ejected per unit of time, or to raise the exhaust velocity considerably, or to increase both simultaneously.

An exhaust velocity approaching the speed of light would be the ideal, but it is unlikely that men will ever succeed in creating substances developing combustion temperatures of tens and hundreds of thousands of degrees, and only such temperatures, and the exhaust velocities corresponding to them, would make it possible to dream of rocket speeds, giving men the chance some day to escape into the interstellar space and visit other worlds.

So, in order that the whole problem should not become hopelessly pessimistic, chaining man forever to the limits of his nearest neighbours or, at best, within the Solar system, engines must be created, based on quite different principles.

In recent years, with the building of charged-particle accelerators and the development of plasma generators that convert heat directly into electricity with no need for boilers or turbo-generators, and at high efficiency (70 per cent and over), intensive work has begun on what are called ionic propulsion or ion-plasma jet engines for rockets. Their main attraction is the possibility of converting a substance first into a high-temperature plasma, i.e. of ionizing a gas, and then accelerating the ions produced to velocities comparable with that of light, thereby increasing the thrust of engines as many times as the exhaust velocity of the ions exceeds that of the gases produced by the combustion of ordinary chemical fuel, if given equal quantities. Hence there would be a considerable increase in the lift, velocity, and range of rockets, and other advantages no less decisive.

The mass of a proton is 1 836 times that of an electron, while the mass of an ion, in turn, exceeds the mass of a proton by as much as the atomic weight of the fuel used exceeds that of hydrogen. Consequently the most important thing in designing an ion engine for the foreseeable future will be to increase the mass of the ions ejected from the rocket.

But our present-day charged-particle accelerators, even the superpowerful ones, are of little use for the purpose, for it is not a fine invisible ray, even of heavy particles, with a current measured in micro-amperes, that is to be accelerated, but a powerful flux of particles, measured in hundreds and thousands of amperes and maybe even in millions.

It is not easy to construct accelerators of such high current intensity.

To make it possible to ionize a fabulously large number of atoms of gas, and then accelerate the mass of positively charged particles obtained to velocities around 10 000 or 100 000 kilometres a second, it would be necessary to mount powerful energy sources on a rocket, whose weight and volume would naturally eat up much of the advantage of the enormous gain in exhaust velocity.

But scientists have calculated that the game is definitely worth the candle. As a result of long research several working models of such engines have been developed.

The design of an ionic propulsion engine is extremely simple. Its main part is an electric generator creating a strong high-voltage electric field. Positively charged ions can be produced from gases like hydrogen or helium, or the light metal caesium, or other substances capable of being ionized, i.e. of losing electrons, at comparatively low temperatures of the order of 2 000°-5 000°C. On entering the electric field of the accelerator, the ions are accelerated to cosmic velocities and then ejected from the tail unit of the engine, building up a jet thrust.

This thrust is not large compared with that of existing rocket engines burning chemical fuel, so it would be better to launch rockets, powered by an ionic propulsion engine, not from Earth, but from an orbit around Earth into which they had been put by means of an ordinary multistage rocket.

Once launched into space, however, a rocket powered by an ion-plasma jet engine could work for days and weeks, and in the future (when it is possible to use atomic power unit) for years.

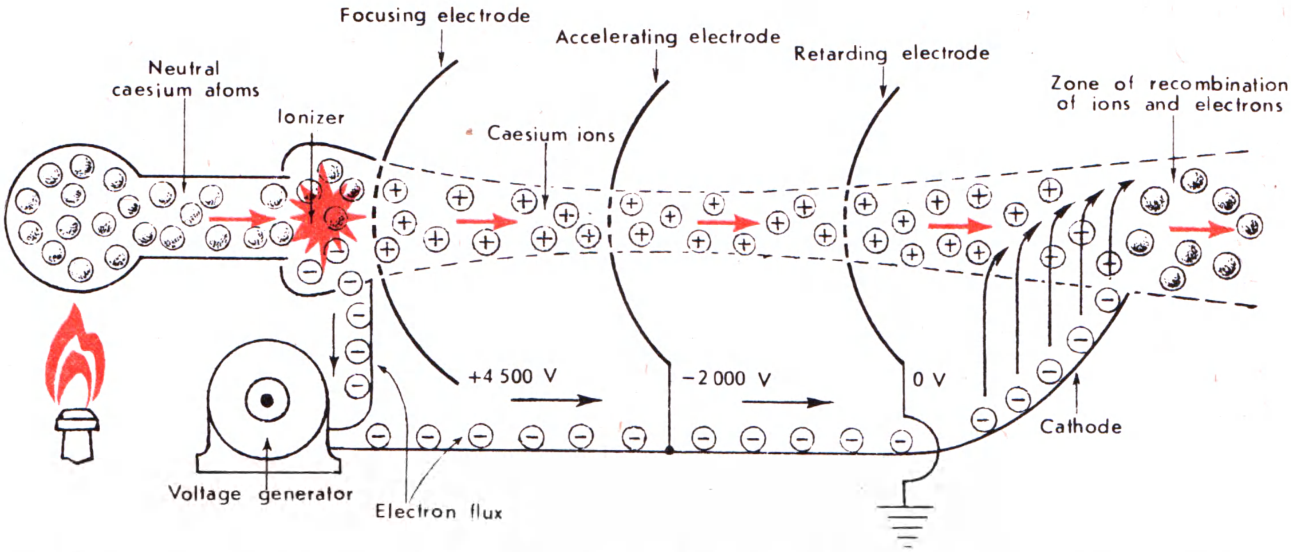
Suppose a spaceship weighing 1 000 tons has been put into orbit. An ionic propulsion engine developing a thrust of only about 100 kilograms (which is more than modest, compared with the weight of the ship) would be able to impart an acceleration to it of about 6 000-7 000 kilometres a day, until it attained a speed around 40 kilometres a second or three or four million kilometres a day. For such acceleration the consumption of fuel (ionized gas) would be only around six kilograms an hour.

This velocity is far below that of the ejected particles, let alone of light. But it could be increased as the density of the flux of particles accelerated in the beam of the linear accelerator rose, taking into account that more than one accelerator could be installed in the rocket, and more compact types of accelerators employed.

On long flights, when the rocket could be accelerated gradually, other sources of power could be used such as thermoelectric or solar batteries.

Photon Rockets

Quantum theory explains light as a flux of photons moving in space in ac-



The principle of an ion-plasma jet engine

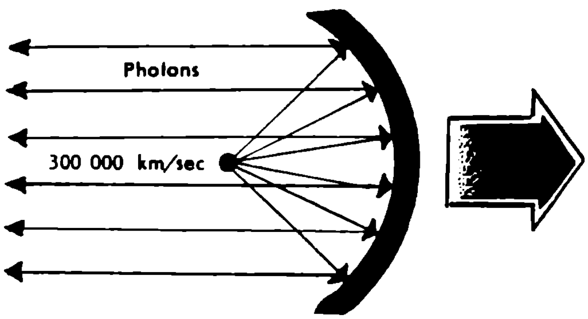
cordance with the laws governing the propagation of electromagnetic waves. Since light as a wave process has a wavelength, oscillation frequency, and a constant velocity of propagation of 300 000 km/sec, the photon, as the particle of light, must possess a mass related to its energy.

At the moment a photon is ejected from a substance, the latter receives an impulse in the opposite direction equal to the impulse of the ejected photon. If the mass of the particle of substance were equal to that of a photon, it would move in the opposite direction with a velocity equal to that of the ejected photon.

Now imagine an incredibly bright searchlight suspended in a vacuum. Under the effect of the recoil thrust of the photons ejected from it the searchlight would begin to move in the opposite direction to its beam at a velocity as many times slower than light as its mass is greater than that of ejected photons. The searchlight would be a kind of light propelled engine, whose movement was based on the recoil thrust of emerging flux of photons, in other words, a photon rocket.

But, of course, a photon has no rest mass. The thrust of a photon propulsion engine, therefore, could not be calculated by the methods used to determine that of engines working on chemical fuels or ions in the same way as it is impossible to calculate how many kilograms of photons would need to be ejected from the exhaust nozzle of such an unusual engine in order to accelerate a rocket weighing, say, 100 tons to a certain speed in a definite period of time. The thrust of a photon engine can only be estimated by the amount of energy the beam of light accelerating our imaginary rocket would possess.

None of the sources of light known to science today is suitable for this purpose, since even the best of them convert only 20 or 30 per cent of the energy consumed into light. In turn, the efficiency of even the most perfect sources of energy obtained by burning fuel rarely exceeds 38 to 41 per cent. The nuclear fission of uranium or thorium liberates 2.5 to 3.0 million times more energy than the combustion of fuel. But only 0.5 per cent, or half of a hundredth part of the energy of the material



The principle of the idea of using the pressure of light as a source of motion

is released. Even a thermonuclear reaction of fusion of light atoms into heavier (hydrogen into helium) yields only 0.5 per cent of their latent energy.

Only one process is known in nature, in the course of which the whole 100 per cent of the latent energy of matter is released. That is pair annihilation, the mutual destruction of two elementary particles, like an electron and its antiparticle the positron. This reaction liberates the entire energy of the electron-positron pair; both their kinetic energy and the energy connected with their rest mass is turned into the energy of photons. According to Einstein's famous equation of mass and energy $E=mc^2$, the own rest mass of an electron or positron corresponds to an energy of 0.51 MeV. So the total energy of the two photons resulting from the collision and annihilation of an electron and positron is $0.51\times2=1.02$ MeV.

Therefore, to make use of the principle of reaction propulsion by means of a photon rocket, it will first be necessary to convert material into elementary particles and their anti-particles (electrons and positrons, protons and antiprotons and so forth), and, then to guide the two separate fluxes of these particles into some 'combustion' chamber, where the energy of their mass would be turned in the course of annihilation into light, visible or invisible.

All our reasoning here was intended to show how fabulously vast are the quantities of energy that man will have to deal with in order to take advantage of the sole possible rocket that could theoretically fly with a speed near to the velocity of light.

But of course any source of light, except a laser, emits beams uniformly in all directions, and these can be concentrated into a parallel beam in one direction only by means of a concave mirror. But no ideally smooth surface exists in nature that could reflect light with 100 per cent effectively, between 2 and 3 per cent of its energy would be absorbed by the material the mirror was made from.

The mirrors of searchlights and cinema projectors with high-intensity electric arcs are cooled by running water or a current of air. But where millions and thousands of millions of kilowatt-hours of energy are involved, concentrated onto a quite limited area, the amount of energy absorbed by the material of the mirror would be expressed in millions of kilowatt-hours, and the mirror would evaporate instantly, no matter what it was made of.

The next 'but' is even more difficult. Let us assume that we have a wonderful machine, a superpowerful accelerator, that makes it possible to produce an astronomical quantity of anti-particles of some sort (positrons, anti-positrons, etc.) or even anti-substances (anti-deuterons and so on).

Whereas the life of the main elementary particles, the proton, electron, and neutrino, is infinite, their anti-particles live only a millionth or a thousand millionth of a second before they meet the first random particle, for everything around us consists of such particles, the parts of apparatus, tubing, 'combustion' chambers, and even the molecules of gas left inside accelerators after they

have been exhausted to the maximum.

So anti-particles are annihilated almost as soon as they are born, everywhere except where we want it, i.e. in the 'combustion' chamber at the focus of our gigantic ideal mirror. It is even difficult at present to conceive any physical method of isolating anti-particles from their antagonists.

The other 'buts' are even more complicated, and hardly worth going into here. But it would be a mistake to think that the photon rocket is a beautiful but vain dream. It seems impractical to us from the standpoint of present-day science and of any developments that can be expected in the foreseeable future. But in five, or ten, or fifty, or a hundred years some unexpected, breath-taking and incredible discovery may be made in physics.

And it might even be a photon rocket. Or it might not.

But if and when it comes, one of its sources of inspiration will undoubtedly be the dream of an engine that could carry men to other stars at a speed close to that of light.

A Nuclear Battery

Now is the most appropriate moment, perhaps, for you to ask quite rightly, where, fantastic stories apart, is that little mysterious box the old writers talked about that could supply power to a large ship, a submarine, a flying machine, or a space rocket?

From the preceding chapters we know that the energy released by the nuclear fission of a handful of U-235 or Pu-239 is equal to the electricity generated by a large power station in several days of continuous operation.

So the dream of our fairy tales may come true. But the mysterious source of inexhaustible energy that would fit into a match box still does not exist.

The trouble is that the comparatively small quantity of the wonderful nuclear fuel (uranium or plutonium) must be put away inside a heavy, cumbersome nuclear reactor, a box of the size of a big house, with concrete walls as thick as a fortress.

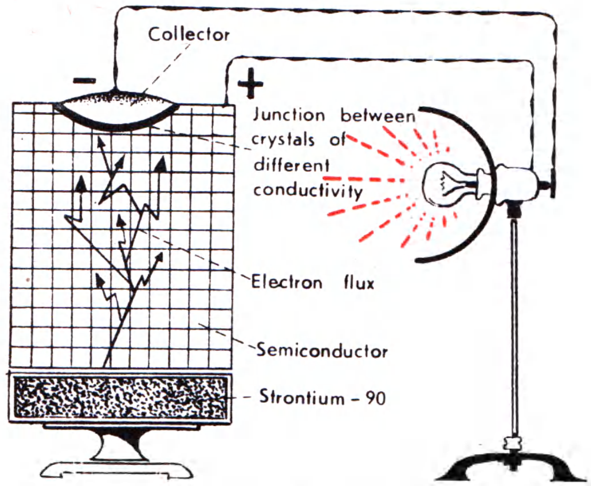
Now, when much of the work had been accomplished, and the most powerful force in nature was in the hands of man, it was only natural for another, quite legitimate desire to arise, to clear away the thick concrete walls from around this force, to remove the heavy load, weighing hundreds of tons, from the wonderful new source of liberated energy. And, then...

But now? Is it really a fact that nothing can be done about it here and now? Not even a first tiny step in that direction?

The step has already been taken. A small nuclear electric battery has been built no bigger than 0.3 cm^3 in volume, and this baby can generate electricity continuously for twenty or thirty years.

And how is it built?

We have already mentioned that nuclear fission of uranium-235 or plutonium produces very many different radioactive fragments, elements from the middle of Mendeleev's Table like barium, iodine, strontium, lanthanum, and so on. In the course of their radioactive disintegration these fragments emit beta-particles or electrons, some quite a few, but in a short time, but others a small number over a long period of time. And a third sort not only eject electrons, but also emit penetrating gamma-rays against which only concrete metres thick gives protection, even when the emitting source is no bigger than a speck of dust. The flux of electrons, however, can be arrested by an aluminium cover one millimetre thick. So it is possible therefore, to select isotopes that do



Scheme for a low-voltage electric cell consisting of a wafer of strontium-90 and a semiconductor rectifier

not emit dangerous gamma-rays but do eject quite large numbers of electrons for a comparatively long time.

After painstaking investigations it was found that the radioactive isotope of strontium Sr-90 was most suitable for this purpose. Its half-life is 24 years, its beta-emission is 0.61 MeV which is quite sufficient, and it does not emit gamma-rays. So we have a piece of radioactive material that emits electrons; but that is not yet a battery. For a source of electricity to yield up its energy, that is to say, to carry an external load, there must be two poles or electrodes with a difference of potential between them.

And what difference of potential can be obtained with a piece of Sr-90, if the electrons ejected by its nuclei fly off at random in all directions? As many will fly in one direction as fly in the opposite direction, so that a difference of potential is impossible to obtain in spite of the enormous number of electrons emitted by Sr-90.

It turns out that it is not enough to have just one source of electrons. The movement of the whole mass of electrons or escaping beta-particles bearing electric charges must be orderly, that is directed mainly in one definite direction.

That can be brought about by passing the flux of electrons through a device in which electrons moving in one direction would meet the least resistance, while those moving in the opposite direction would meet a very high resistance. Devices that do that are known as rectifiers, detectors, and valves.

Nowadays certain crystals known as semiconductors have become very important in science and engineering. All kinds of devices are made from them, semiconductor devices, and rectifiers, and amplifiers, and generators. These crystals have a very remarkable property that other substances do not possess. When electrons of large energy (or velocity), like those from radioactive Sr-90, pass through a semiconductor (say, silicon or germanium), they knock many other electrons out of the shells of its atoms, and these secondary electrons, acquiring just as high velocity, in turn knock a third generation of electrons out of the atoms of the semiconductor, and so on.

Something like a chain reaction takes place, and the number of electrons knocked out of the semiconductor grows like an avalanche.

As a result, each electron initially emitted from the Sr-90 radioactive source reaches a rectifying device (the point of contact of two crystals that conduct electrons in different directions), accompanied with the host of electrons that it and its fellow-travellers have knocked out of the semiconductor. And when you consider that a tiny piece of Sr-90 emits millions of electrons a second, you can see that a quite appreciable electric current will flow through the rectifier in one direction only So we

have a tiny cell with a voltage of half-a-volt and a power of one microwatt.

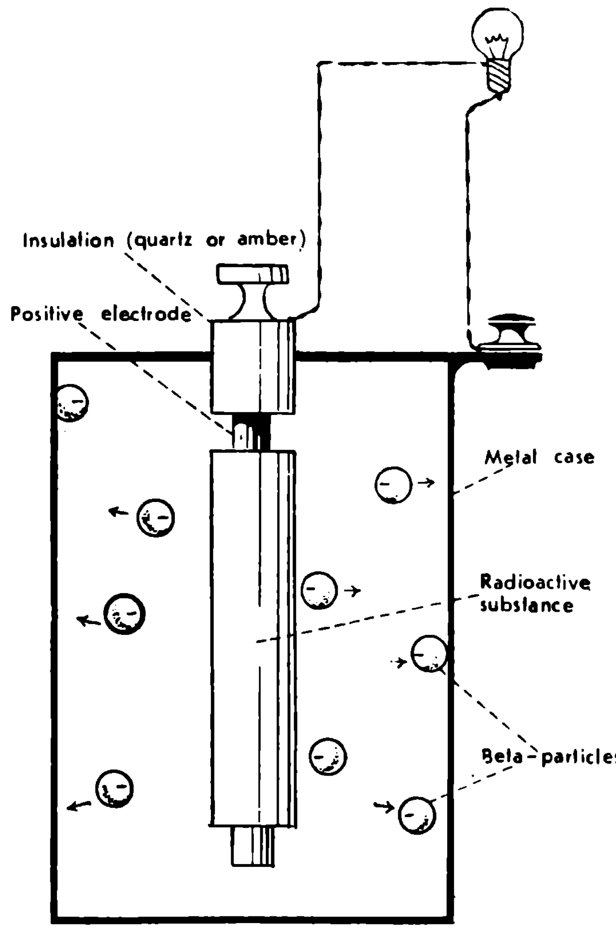
That is very small, of course; but then one cubic metre consists of one million cubic centimetres, and an enormous number of these tiny cells can be packed into that volume, so we can get a whole battery supplying hundreds of amperes of current at 0.5 V for 24 years. And that, after all, is not bad.

In time, of course, it will be possible to reduce the size of the battery elements to a tenth or perhaps a hundredth what they are now, and to raise the current intensity by using materials that emit a larger number of electrons. Such a battery would be both heat and cold resistant and would require no attendance or servicing to speak of. So, you see, the dream of an atomic electric battery is quite fascinating.

It is possible to make such a battery in a rather different way by putting an electrode coated with a radioactive substance that continuously emits negatively charged beta-particles (electrons) inside a metal case.

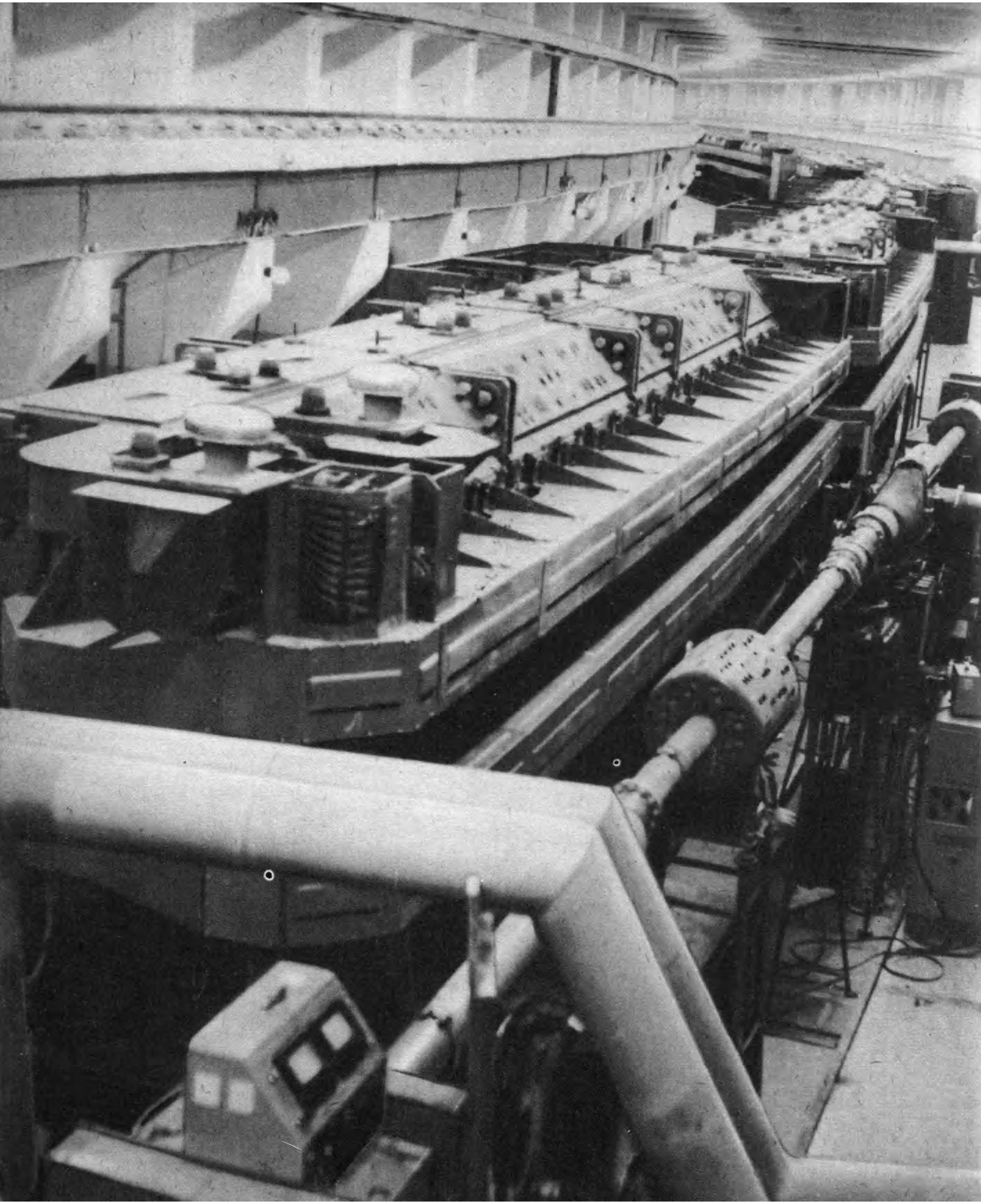
Because it loses two negative charges with every beta-particle ejected, the central electrode becomes more and more positively charged and the outer case becomes more and more negative. Now if air is evacuated from the space between the two electrodes, and they are properly insulated from each other, the potential across them could become very great, around a hundred thousand volts. The intensity of the current, of course, would be insignificant, a mere hundredth of a micro-ampere. But the cells could be connected in parallel and in that way current of the desired intensity obtained.

The inestimable advantage of atomic batteries is that the initial material for making them would be the fission products (dangerous waste) produced in large quantities in nuclear reactors.



Scheme for a high-voltage atomic battery

An atomic battery employing a silicon or germanium semiconductor rectifier also can work on gamma-rays. In it a flux of electrons would be created by gamma-rays knocking electrons out of the nuclei of the germanium or silicon. But because of the high penetrating power of gamma-rays, it would be necessary to enclose this battery in thick concrete or lead biological shielding, but it could be employed where weight did not matter much.



Chapter Thirteen

WHAT ARE NUCLEAR FORCES?

A Strange Game

Imagine that you are at a football match and that the longer you watch the game the more puzzled you are. Instead of scoring against their opponents some of the players are doing their best to kick the ball into their own goal; at most dangerous moments the goalkeeper leaves the penalty area to talk with the manager; instead of penalizing players who break the rules, the referee punishes those who don't. You can see the field, the goals, the ball, you know the teams that are playing, but are unable to make out what the rules of the game are, by what laws it is governed. But it is possible that if you watch such a mad game long enough you will ultimately be able to guess what the rules are.

But now you find yourself on a neighbouring pitch, where football is also being played. Here the game goes as it should, all the rules are observed, for everyone knows them; there is only one snag—you cannot see the ball. The players are using an invisible ball, and judging from their behaviour they even seem to see it and to control it. Here the rules of the game seem clear and understandable, but is the ball large or small? It is not clear what it is played with. Is it light or heavy? Or is there a ball at all?

Something similar happened to the physicists who tried to understand what exactly went on inside the atomic nucleus, what forces prevailed there, and what laws governed them.

We already know that the electric forces that attract negatively charged electrons to the positively charged atomic nucleus should force the positively charged particles or protons concentrated in the nucleus to scatter with enormous force.

But, contrary to all known laws of physics, the protons within an atom do not fly apart, but are held together for some reason so strongly that enormous energy must be used to pry them apart.

What are these forces?

Electrical? If the positive charges of half the protons in the nucleus were replaced by negative ones, so that repulsion gave way to attraction, the forces binding the particles together by attraction would prove to be a fraction as strong as the forces that actually hold the like charged protons together within the nucleus.

Consequently, these forces are clearly not electrical. And moreover, how could electrical forces hold together neutrons in the nucleus which have no charges at all?

Perhaps it is the force of gravity? But gravity proves to be even less acceptable, since the gravitational forces acting between two particles in an atomic nucleus are 10^{37} times weaker than the forces actually holding them together.

Then, what are these mysterious, incomprehensible forces?

When scientists first began to busy themselves with electrons, they already knew exactly what forces operated in the 'game', which were the electrical forces of repulsion and attraction. Only the laws governing their behaviour were not known.

In order to explain all the most complicated aspects of electron motion and of the interaction of electrons with positively charged particles, and in order to explain the properties of the atom as a whole (its size, its chemical properties and behaviour, the light it emitted when the energy level of its electrons changed; the motion of its electrons within it, etc.), physicists were driven at the time to working out a completely new theory of the motion of particles in the microworld and developed quantum mechanics, which at last explained the rules of the strange and incomprehensible game as bewildering as the football match described at the beginning of this chapter.

When it comes to the atomic nucleus, we also can understand the laws governing it, for it is still a matter of quantum mechanics. But we do not know what forces are involved in this intranuclear 'game'.

What Attracts Electrons to Protons

According to Coulomb's law, formulated back in 1784, the force operating between two electric charges depends on the magnitude of the charges and the distance between them, being inversely proportional to the square of that distance.

Much later, as a result of the work of Faraday and Maxwell, a fact of the greatest importance for modern physics was established, that if the distance between two electric charges is altered in some way, say by moving one of them, the change will not affect the other charge at the moment of the shift, but only after an interval equal to the time needed for a beam of light to cover the distance between them.

This fact made it possible to relate the phenomena of electricity and light, and showed that the electromagnetic field surrounding a moving charge was propagated from it at the velocity of light.

The researches of Planck and Einstein proved that an electromagnetic field, like matter and electric charges, is not continuous, but corpuscular in structure. The minimum amount of electromagnetic energy forming a field was called a quantum or photon.

A quantum of radiation or photon

can exist and be propagated only at the velocity of light, i.e. at 300 000 kilometres a second. And that is the speed at which the effect of an electric charge is transferred to another one.

Modern physics considers that the forces exerting an interaction between charged particles are photons continuously emitted and absorbed by the particles. And this continuous exchange of photons between two charged particles also creates the forces of electric repulsion and attraction.

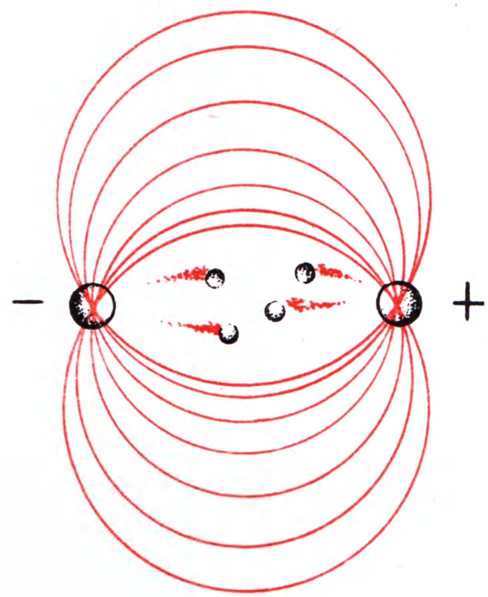
The new theory fits the experimental facts obtained by physicists up to now more closely and more exactly than any other. And on its basis it has been calculated with great accuracy that the structure of the simplest atom of matter, hydrogen, consists of just two particles, a proton and an electron.

But when we pass to explaining with what forces the elementary particles comprising the atomic nucleus affect each other, and what is the nature of these forces, we run up against great difficulties in trying to represent the nature of these special intranuclear forces, since neither the habitual notions of schoolbooks nor such 'convincing' and 'self-evident' analogies as the memorized formula: 'unlike charged bodies attract each other, and like-charged bodies repel' are of any help here.

As regards their action and properties intranuclear forces are much more complicated than the electrical forces of attraction and repulsion, or any other forces known to science.

The interaction between two nuclear particles would seem to depend not only on the distance between them but also on their velocity and relative direction of spin.

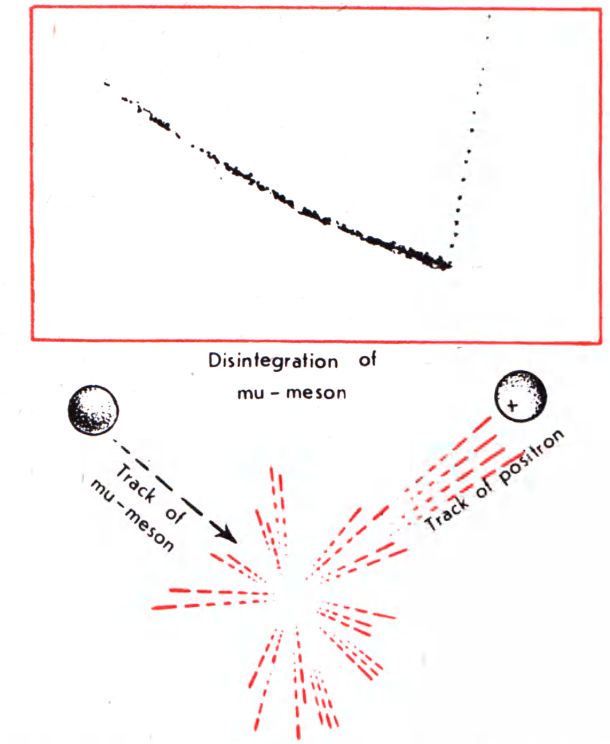
It is likely that there are forces that affect three, or four, or even more particles at once. And these forces, it should be particularly noted, are completely independent of the electric charges of the particles. Protons and protons, neutrons and neutrons, and protons and neutrons are all attracted to each other with approximately the same force.



Two electrically charged bodies interact by continuously exchanging photons, resulting in the formation of electric forces of attraction or repulsion between them

The most interesting thing about internuclear forces is their exceptionally short range or radius of action. The nuclear forces that attract two protons to each other at a distance of, for example, 2.6×10^{-13} cm are ten times as powerful as the force of repulsion acting between them. But if this distance is only doubled, the intranuclear forces of attraction are already only equal to the electric force of repulsion. And if the distance between them is increased 25 times, the electric forces of repulsion begin to exceed the intranuclear forces of attraction by a million times.

On the other hand, there are reasons for assuming that with even shorter distances, less than 0.5×10^{-13} cm, the



What happens to a mu-meson in a Wilson cloud chamber. The track of a slow mu-meson begins in the left corner of the chamber and it becomes 'fatter' and 'fatter' since it is being gradually delayed by collisions with atoms of the gas filling the chamber. When it is decelerated to the energy at which its steady state becomes disturbed, the mu-meson explodes and splits into a fast positron and two neutrinos, depending on its initial state. The neutrinos leave no tracks on the photograph, since, having no charge, they do not ionize the gas

intranuclear forces abruptly cease to attract and turn into even stronger forces of repulsion.

Intranuclear forces have another important property; the interaction between nuclear particles also has the character of an exchange.

And here we come up against a fact that indicates that the interaction between nucleons, e.g. between a neutron and a proton, must be effected by means of material particles of an electromagnetic character resembling the photons, through which the interaction between electric charges occurs. This idea was first suggested by the Soviet physicist and Nobel prize winner, Igor Tamm.

And what are these particles?

Enter a New Particle, the Meson

In 1933 the Japanese physicist H. Yukawa, analysing the theoretical and experimental data available, advanced a number of new ideas about the nature of nuclear forces. In his view, the role of a binding quantum in the atomic nucleus was played by a new material particle, which he called a meson. Yukawa also predicted the properties of the particles that should be exchanged between protons and neutrons in order to bring into effect the tremendous forces that act across short distances and only within the limits of the atomic nucleus. These exchange particles themselves should interact strongly with protons, neutrons, and nuclei, independent of their charges.

From the general principles of quantum mechanics it follows that the forces acting over long distances, like electric forces, can be transferred by particles having no rest mass, i.e. by particles that can only exist when they move with the speed of light. Photons, as we already know, are particles of this kind. The entire mass of a photon

manifests itself and is associated with the fact that it moves with the speed of light.

But, according to the same laws of quantum mechanics, forces acting over short distances should be transferred by particles with mass even at rest and the shorter the range of action of the nuclear forces, the greater this mass should be.

For forces with a range of action around 10^{-13} centimetre (two nuclear diameters) the mass of these particles should be about 200 times as big as that of an electron.

For these particles to be able to effect any exchange between the nucleons of a nucleus, they would need to be electrically charged. When a proton and neutron interact, the proton would emit a positively charged meson which would be absorbed by the interacting neutron; and in the process the proton would lose its positive charge and become a neutron, while the neutron would acquire a positive charge and become a proton.

The same thing would happen when a neutron emitted a negative meson absorbed by a proton.

The idea of the existence of both positive and negative mesons was postulated by Yukawa in conformity with the general principles of modern physics that for every positively charged particle in nature there must be a corresponding particle carrying a negative charge.

Yukawa's particles, given the name of mu-mesons or muons, were first identified in cosmic rays in 1936. They had a mass 207 times that of an electron (or positron).

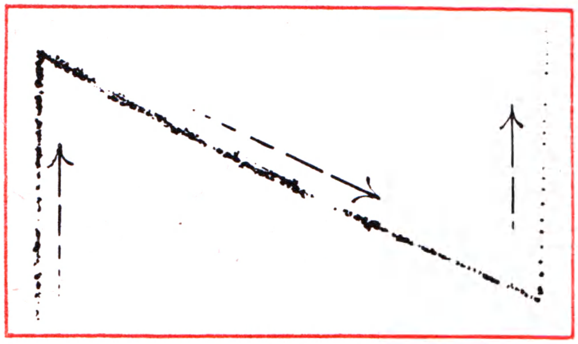
But it was soon found that these particles behaved in ways quite different than had been expected. Mu-mesons were indifferent to atomic nuclei and only responded to the electric charges of protons. Their interaction with protons was so weak that in no way could they act as bearers of intranuclear exchange forces. In addition, they were extremely unstable. Their average life was a mere 2.2 millionth of a second. Depending on its charge, the disintegration of a mu-meson was always accompanied with the appearance of an electron or positron. And the energy released by its disintegration showed that at least two other particles should appear, without charges and with a mass many times smaller than that of an electron (1/2 000). These particles were the neutrinos we mentioned in an earlier chapter.

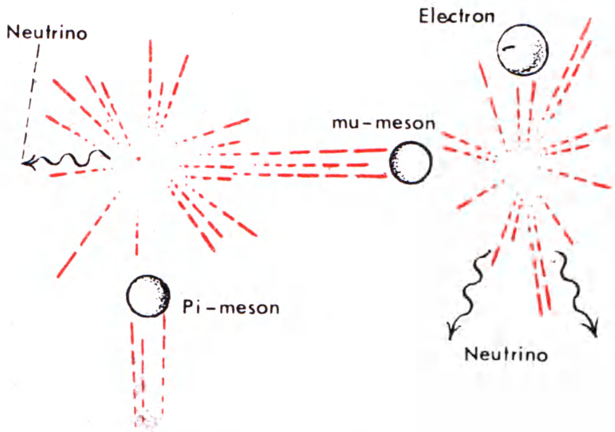
The Meson Family

The mesons, which are actually responsible for the existence of intranuclear forces, were discovered in 1948 by Powell, Occhialini, and Lattes (an Englishman, Italian, and Brazilian) and called heavy pi-mesons (or pions). Their mass was 273 times that of the electron.

The conditions in which pi-mesons are formed, exist, and subsequently become transformed into other particles are very complicated. Pi-mesons first detected in cosmic rays, come to a stop in 2.5×10^{-8} second because of deceleration in the cloud chamber, and break up into two particles, a mu-meson and a neutrino. To make it clearer why this happens, let us recall that when a particle is at rest (a pi-meson in this case) it possesses only its proper energy related to its mass.

The disappearance of a pi-meson opens up access to its intrinsic or proper energy, part of which is expended in creating the mass of the lighter mu-meson and the rest of which is converted into energy of motion, or kinetic energy, with the result that the mu-meson and neutrino just formed fly apart with a tremendous velocity (energy). The kinetic energy acquired by the mu-meson and





Being slowed down in a substance, a pi-meson comes to a stop and disintegrates into two particles, a mu-meson and a neutrino. The mu-meson is then also slowed down by collisions with the nuclei of other atoms and breaks up into an electron and two neutrinos

neutrino is the exact equivalent to the residual energy, which is why the particle can only disintegrate spontaneously into lighter particles.

Mu-mesons also disintegrate, forming an electron and two neutrinos. And a fast mu-meson, hitting an atomic nucleus, can destroy it.

Heavy pi-mesons, unlike other mesons, interact very strongly with atomic nuclei. It was they that proved to possess the properties predicted by Yukawa in 1933, i.e. to be *quanta of the nuclear field,* just as photons are *quanta of an electromagnetic field.*

But the theory suggested by Yukawa did not fully explain some of the peculiarities and fine points of the action of intranuclear forces. For everything known about these forces to fit more or less accurately, there should also be another uncharged neutral pi-meson, responsible for the exchange reaction between two protons and between two neutrons. A proton, of course, cannot absorb a positive meson, since it is unable to acquire a second positive charge, that is to say, no charged meson can effect the exchange reaction between two protons.

The existence of the neutral meson, in particular, explains why the action of intranuclear forces is independent of the charges of the particles that make up an atomic nucleus.

Neutral mesons were soon identified in cosmic rays, thus making the picture complete. Their mass was 264 times that of an electron, and they had no electrical charge. Their life is also very short, less than 2×10^{-16} second, and they disintegrate into two photons.

Thus, the formation and existence of intranuclear forces are ensured by three kinds of particle emitted and absorbed by protons and neutrons. These are the heavy positive and negative pi-mesons that are responsible for the existence of exchange forces between neutrons and protons, and the heavy neutral pi-mesons that are carriers of the exchange forces acting between similar nuclear particles, between two protons or two neutrons.

In short, the meson theory adequately explains all the features and fine points of the action of intranuclear forces, which were still difficult to imagine distinctly because of their unusual nature, contradicting everything in previous experience and thinking of physicists. It looked as if the invisible ball used in the intranuclear 'game' described at the beginning of this chapter had at last been discovered.

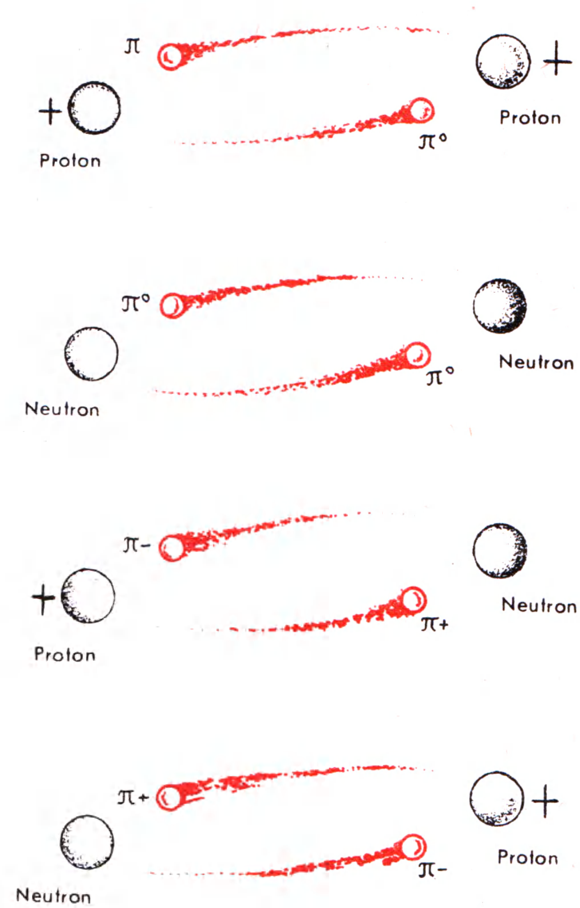
Before long a whole family of even heavier mesons, i.e. particles heavier than pi-mesons but lighter than protons, had been identified in cosmic rays, and later by means of superpowerful particle accelerators. Particles of a mass 966 times that of the electron were detected, for example, and given the name of K-mesons. Our drawing below illustrates the appearance and successive transformations of this quite unusual particle. A still unknown cosmic particle, most likely a proton of enormous energy, possibly of tens or hundreds of gigaelectron-volts (GeV) passing through the atmosphere that acts as a kind of gigantic protective armour for our planet, smashes to smithereens the nuclei of substances encountered. This random encounter results in the appearance of a fragment, a superheavy meson. After flying a certain distance, this particle disintegrates in 0.85×10^{-8} sec into three pi-mesons, which in turn soon break up into mu-mesons that then break down into electrons and neutrinos.

As with pi-mesons, there are also neutral K-mesons.

It is possible that the meson theory of intranuclear forces will turn out to be short-lived, and that scientists will be forced patiently to erect a new theory, to explain the No. 1 puzzle of present-day physics, namely, what are these intranuclear forces?

Superheavy Particles or Hyperons

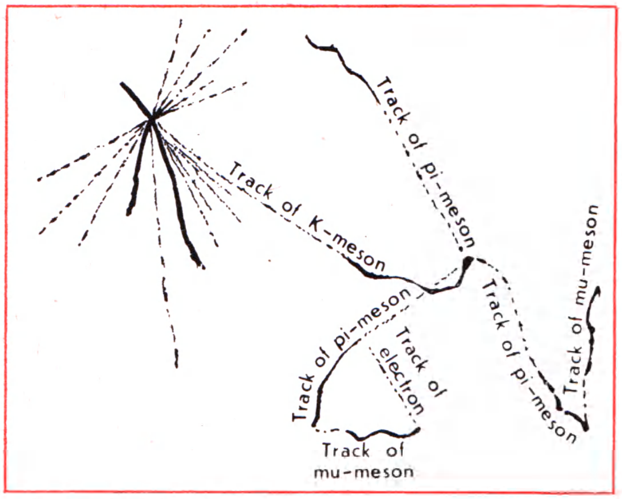
In recent years, again first in cosmic rays, and then in accelerators, particles have been identified whose mass turned out to be even greater than that of a proton. These unstable, rapidly disintegrating particles were given the name of superprotons or hyperons. They may be charged or neutral. For several reasons the neutral hyperon has been studied rather better than the others. Its



A scheme explaining the fine points of the interaction of nuclear particles by means of the continuous exchange of pi-mesons. Interaction of a proton and a proton, or a neutron and a neutron can only occur by means of a neutral pi-meson. A proton and a neutron, or a neutron and a proton interact through the agency of positive or negative pi-mesons

mass is 2 182 times that of the electron, i.e. it is about 340 electron masses heavier than a proton. When it appears, it exists for no more than 3×10^{-10} sec and disintegrates in flight into a proton or neutron and a negatively charged pi-meson.

There are no grounds as yet for considering these particles some new kind of meson. They are too heavy for that. Indeed it is difficult to suppose that a proton and a neutron, on interacting, exchange particles of a mass greater



Schematic representation of the appearance of a heavy *K*-meson and of the course of its subsequent, successive transformations. The dark tracks of the 'star' are those of protons. The finer tracks are those of fast protons and pi-mesons

than that of either of them. When hyperons break down either a proton or neutron always arises, which suggests that a hyperon is a proton or a neutron that has absorbed a considerable amount of additional energy, putting it into an excited state, so that it must get rid of this energy at once; naturally, therefore, it disintegrates into a proton or neutron and a meson.

That picture gives only an approximate idea of the nature of forces acting within the infinitely small volume of the atomic nucleus, the continuous motion and transformations of which conceal enormous energy.

What Can There Be in Common Between a Drop of Water and an Atomic Nucleus?

We already know that the nuclei of heavy elements are very unstable and that they become very excited, on absorbing a neutron, which finally ends either in the 'evaporation' of one or more excess particles, or in splitting of the nucleus (U-235, for example) into two parts.

How could that more or less substantiated and comprehensible explanation be linked with the existence of the powerful forces binding and holding together all the nucleons of a nucleus, forces that would seemingly quite exclude the disintegration of even a strongly excited nucleus?

Unfortunately, there is still no exhaustive explanation of the very intricate mode of action of intranuclear forces. There are only several hypotheses, and even theories, that help to some extent to explain intranuclear processes and make the necessary, if approximate, calculations.

One of these theories is the drop model of the nucleus proposed by the Danish physicist Niels Bohr and the Soviet physicist Ya. I. Frenkel.

Indeed, by the nature of the processes going on inside it, the nucleus reminds one of a drop of liquid. The particles or nucleons of which it is built (protons and neutrons) are pictured as being arranged in the same way as the molecules in a spherical drop of liquid (water, for instance). The electric charges of the molecules push them apart vigorously (and with great force), and as a result they are weakly bound to each other, so that the drop, as a whole, tends to spread or 'run'. At the same time the quite strong surface tension of the outer molecular film of the water tends to keep the molecules together, and the liquid in consequence acquires the only possible shape, that of a spherical drop. Imagine such a drop of liquid cut into two halves; in each half the liquid will be of equal density over the entire volume, which means that the number of molecules in any volume is proportional to volume itself.

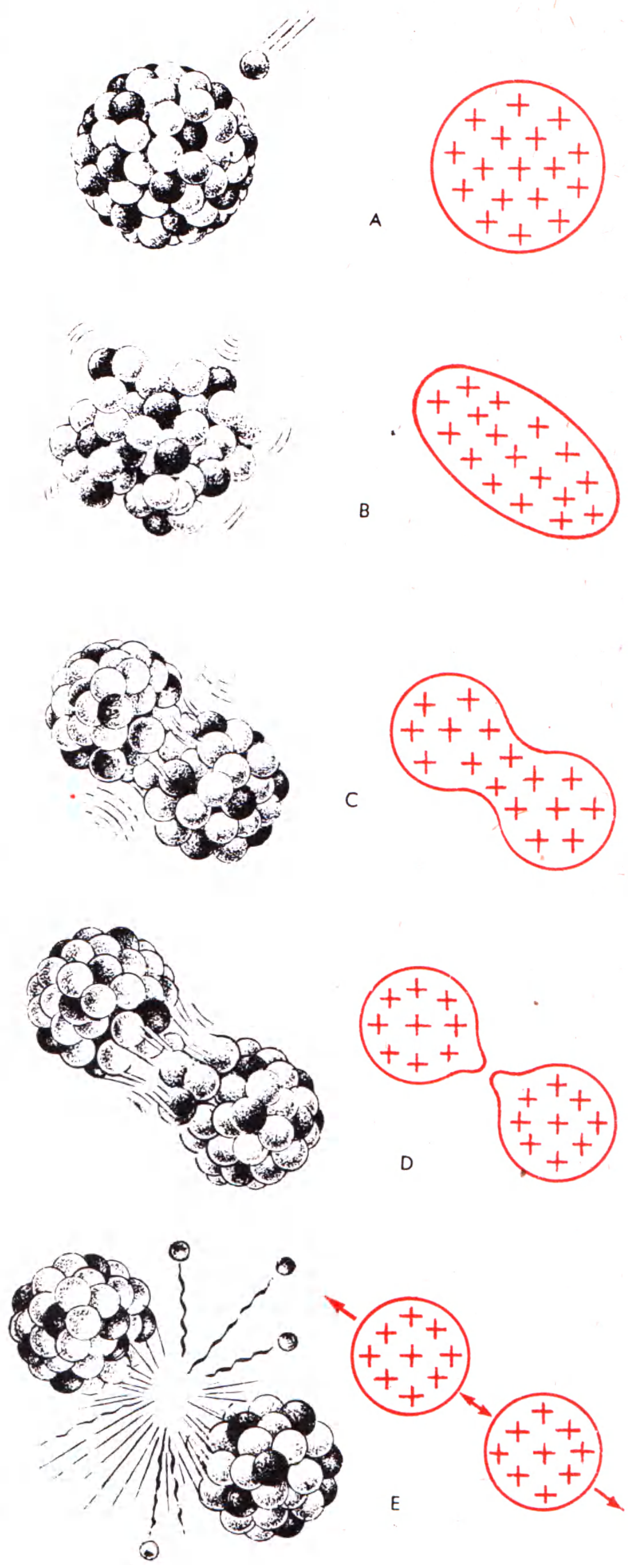
As all research has shown nuclear forces act at very short range. Only

adjacent particles interact in a nucleus, i.e. almost the same as with the molecules in a drop of water. Nuclear forces do not act between distant particles.

If a spherical drop of liquid is made to oscillate, it will pass through a number of states differing greatly, depending on the energy of oscillation, from its initial form. If the energy is low the spherical drop turns into an ellipsoid, then through the action of its surface tension it turns back again into a sphere. But if the amplitude of oscillation is great, the drop may acquire the shape of a dumb-bell, and then a small effort would be enough to break it into two deformed parts, which would at once acquire regular spherical shape.

An excited regular nucleus of a heavy element undergoes about the same series of states during its oscillatory movement. At one of these moments, when the nucleus acquires the shape of a dumb-bell, i.e. when parts of the nuclear 'drop' are squeezed, as it were, out of the range of action of the nuclear forces (and the bunches of positively charged particles, also squeezed to the ends of the dumb-bell, prove to be in exceptionally favourable conditions amplifying their repulsion), the neck between the two bells breaks, and the nucleus splits in two.

If a flat, round rubber box is filled with water, and the box is squeezed in the middle, water splashes out of it,



An electrically charged spherical drop of water preserves its form as a result of an intricate interaction between its surface tension, the intermolecular forces acting between its particles, and the distribution of the electric charges. If these conditions are disturbed, the drop splits. The behaviour of a uranium nucleus can be pictured in a similar way. When the nucleus is hit by a neutron (*a*) it becomes unstable (*b*), stretches until it acquires the shape of a dumb-bell (*c*), then splits into two halves (*d*), that fly apart with tremendous energy (*e*)

because the volume of the deformed box is smaller than when it is round.

And now, if you are able to use the picture described above in purely geometrical terms to visualize the far less figurative 'play' and interaction of the energy levels of particles in the atomic nucleus, you will get something very close to what actually happens in a strongly excited nucleus.

The Puzzle of Particle Interaction

The properties of atomic and nuclear particles are revealed in the course of their interaction.

In everyday life we very commonly employ the notion of 'force' (or 'power'); and we could count dozens of kinds of forces of all kinds, right to 'will-power' and 'by force of habit'. But... the number of genuine forces of interaction between physical bodies differing fundamentally in their nature is not so very great.

Apart from the force of gravity that is of vital importance only when very large masses are involved, only three types of interaction are known, namely *electromagnetic*, *strong*, and *weak*. These terms, of course, are quite arbitrary.

It is a fact that, in spite of their great variety, all electromagnetic phenomena are identified by the interaction of electric charges that are of equal magnitude for all elementary particles be they protons, electrons, charged mesons, or hyperons. This also applies to phenomena involving the emission and absorption of electromagnetic waves and light, and to all chemical and molecular phenomena (in which only the electron shells of atoms play a part).

The main character or 'agent' responsible for the very possibility of these interactions, the intermediary of exchange between charged physical bodies, is the photon, a quantum of the energy of electromagnetic radiation (about which we said quite a lot in preceding chapters).

The term 'strong nuclear interactions' appeared after 1932, when the secret of the inner structure of the atomic nucleus was discovered to consist of elementary particles of a different kind, charged protons and neutral neutrons. It is the strong interactions uniting and holding nucleons together in the nucleus that underlie the nuclear forces, which, unlike electromagnetic forces, have a very small radius of action but a very high intensity. The action of strong forces ceases abruptly at a distance of about two nuclear diameters.

The process of the emission and absorption of the pi-mesons that are interchanged by interacting nucleons, i.e. protons and neutrons, which we have already explained, underlies strong nuclear interactions. But they also manifest themselves in the collision of high-energy particles, in the course of which a fraction of the energy of the particles gives rise to mesons, hyperons, and many other particles.

But some encounters between elementary particles are due to *weak nuclear interactions.* They usually remain unnoticed in the host of strong and even electromagnetic collisions. What we are referring to is the multitude of spontaneous, quiet transformations of various elementary particles that in principle may have nothing in common, such as the beta-disintegration of nucleons (of a proton or neutron), the disintegration of mu-mesons and pi-mesons, the capture of a mu-meson by a nucleon, and the disintegration of other particles.

The processes induced by weak interactions are often referred to as slow, since the time they take is relatively long, although it very often may only last but a few millionths of a second, as for instance, with the decay of a mu-meson.

But in the world of elementary particles that is a very long time indeed, since strong nuclear interactions are characterized by processes lasting 10^{-23} sec.

The disintegration of elementary particles is caused not by an electromagnetic interaction but by especial one involving a neutrino and other light particles. It is a thousand million times weaker than an electromagnetic interaction, although it is far stronger than the force of gravity. And so physicists call it a weak interaction.

The force of gravity between two bodies is universal in nature, and depends solely on their masses and the distance between them and is independent of what materials the bodies are made of, whether of gold or of iron. The electric forces of attraction or repulsion acting between positively and negatively charged particles depend solely on the magnitude of the charges and distance between the particles, and is independent of what particles carry the charges.

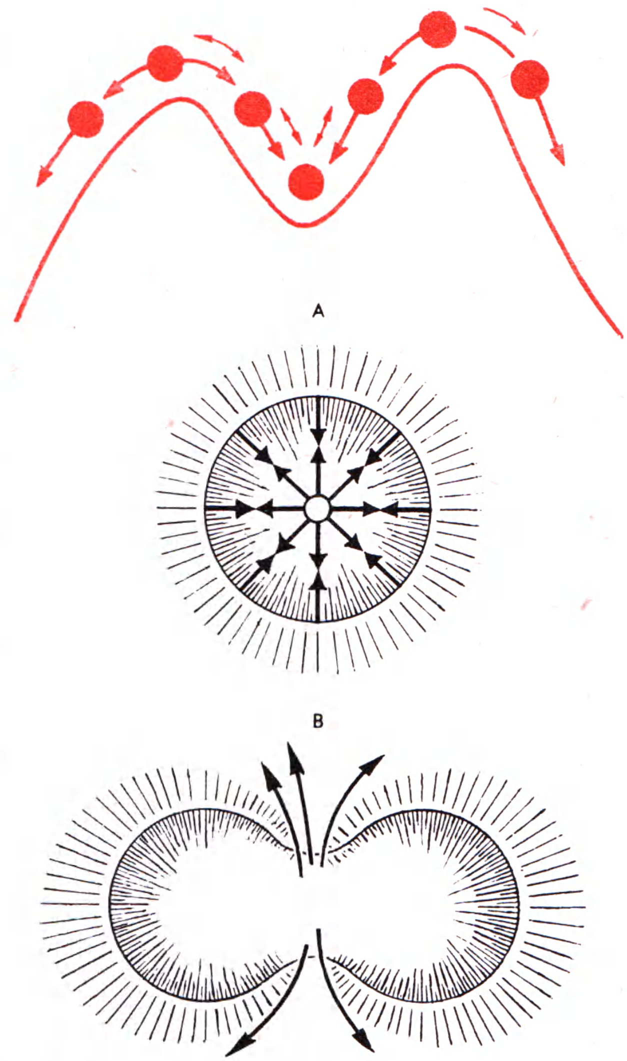
What underlies the weak nuclear interactions of elementary particles?

Before we try to answer that question, let us return to a very important circumstance that has been troubling physicists in recent years.

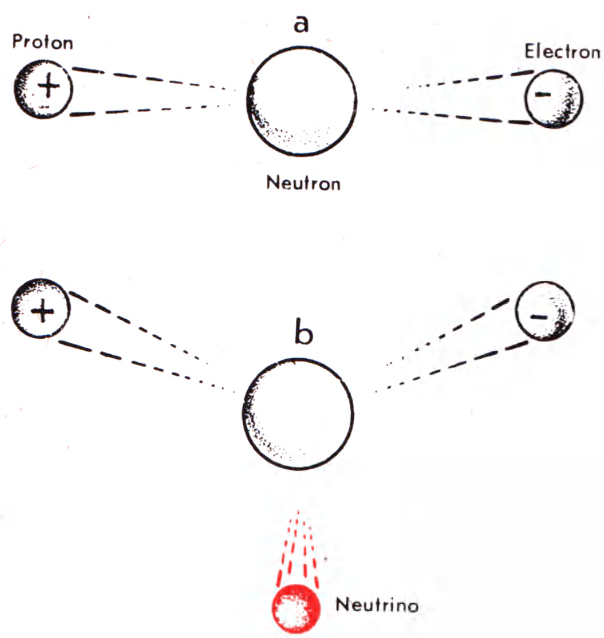
The Elusive Neutrino

In physics the most elusive particle is the neutrino.

Unfortunately, we are not able here to explain the very complicated and subtle arguments and calculations that led scientists to believe and suggest that there should be one more and still mysterious neutral particle, the neutrino. This particle bears no charge and has no rest mass. It can exist only by moving with a velocity very close to that of light, like the photon, which possesses a quantum of electromagnetic energy. In this sense the neutrino is the most wave-like particle.



This is how one can visualize (*A*) the binding forces acting over short distances between the elementary particles or nucleons, that compose an atomic nucleus and (*B*) the electric forces of repulsion acting between positively charged protons. As the distance between the particles increases, the action of the binding forces diminishes quickly



The behaviour of the particles resulting from the disintegration of a neutron which led scientists at the time to suspect the existence of another particle, the neutrino, with rather strange properties: *A*—when a neutron disintegrates into a proton and electron only, these particles should fly in strictly opposite directions in accordance with the law of the conservation of momentum; *B*—in fact, they fly apart at a certain angle, which indicates that the lost momentum is being carried off by another particle, the neutrino

Scientists were led to this conviction by the following experiments. When a neutron decays into a proton and an electron, the particles formed in accordance with the law of conservation of momentum fly apart in opposite directions but in fact they scatter at an angle. This suggested that the lost momentum, and the considerable quantity of energy that could not be accounted for, was carried off by another particle with unusual properties.

The most amazing thing about this particle is its staggering power of penetration. While other particles travel a few decimeters or even metres between collisions in any substance (e.g. iron or copper), the electrically neutral neutrino, that has no rest mass and seemingly moves with the velocity of light, is able to avoid interaction with particles of the substance, and could fly without interference through an iron plate a thousand million times as thick as the distance from Earth to the Sun!

No wonder it has taken scientists more than 25 years of persistent work to become convinced of its existence. It was not until 1956 that they succeeded in identifying a neutrino. Properly speaking it was not a neutrino that was 'caught', but its anti-particle, the anti-neutrino. And it was not so much 'caught' as identified in that rarest of phenomena, its collision with another particle.

We have already said that every elementary particle has a double whose properties are the opposite to its own (e.g. the electric charge). It is more difficult to conceive how a neutral particle differs from its double, also neutral, since neither carries an electric charge, and their masses are equal. The difference between them is so slight, and it manifests itself in such subtle interactions that they can be considered to be truly neutral. But experiments have shown nevertheless, that the neutrino and the anti-neutrino are different particles.

Furthermore, Soviet scientists succeeded in proving that there should be not one, but two, neutrinos—one electronic, and the other muonic (i.e. mu-mesonic), and correspondingly, two anti-neutrinos. The electronic neutrino is involved in all interactions in which an electron participates, and the mu-mesonic neutrino is involved only in a pair with a mu-meson.

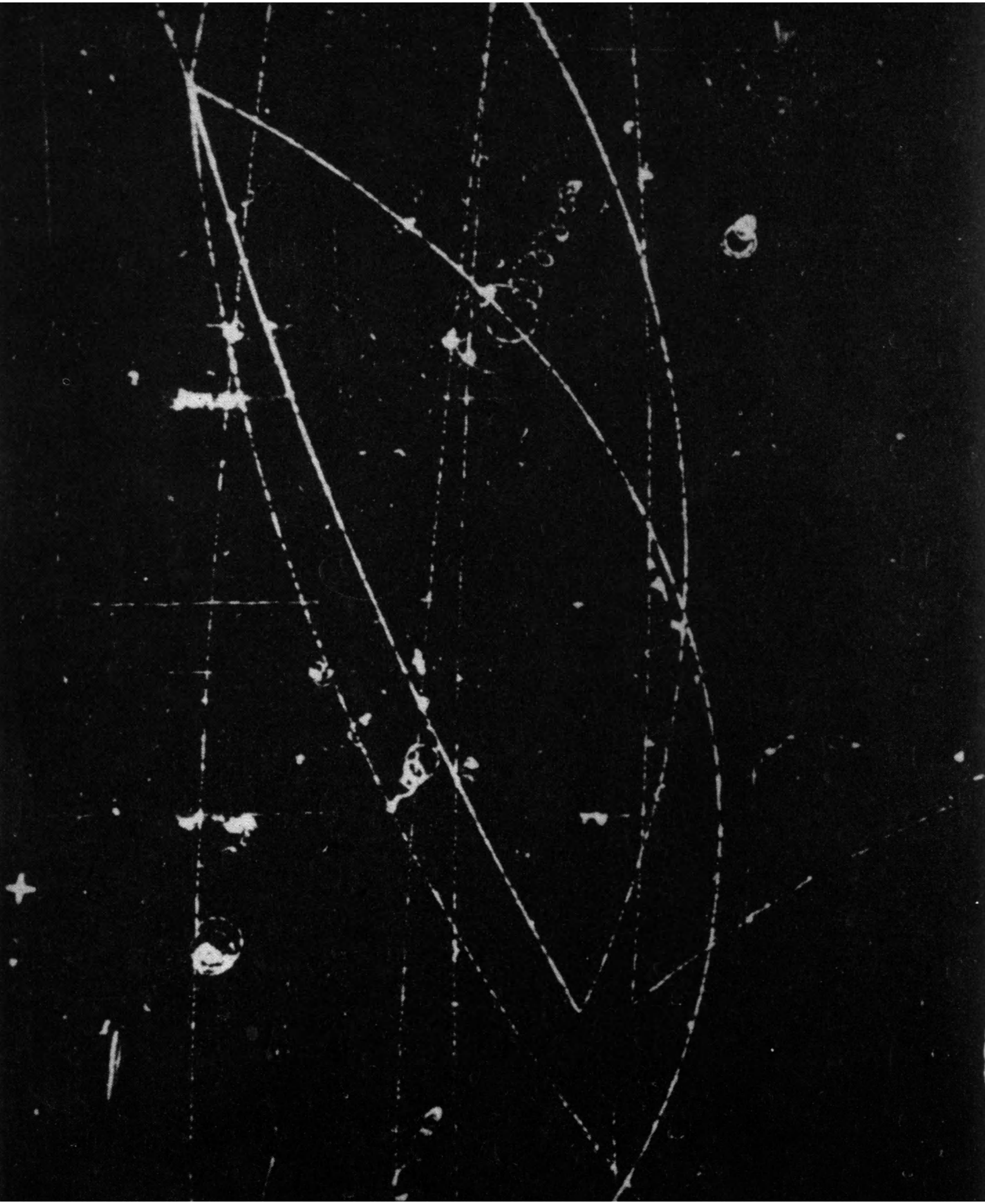
So it was asked, what was the role of the neutrino in all the physical phenomena encountered by scientists in their attempts to understand the nature of matter more deeply.

Is the neutrino a kind of 'patch' used by physicists to try and darn the gaps in their very intricate modern theories where all the loose ends are still not tied up.

Unravelling of the mystery of the neutrino is exceptionally important for evolving a theory of weak nuclear interactions. It is also very important for study of the stars and galaxies. To illustrate, the energy of the flux of neutrinos emitted by the Sun forms a tenth of all the luminous energy radiated by it. When scientists learn how to catch the neutrino fluxes emitted by the stars and galaxies, we shall have another source of information about them in addition to light and radiowaves, which limit the radius of the observed Universe by a mere trifle of several thousand million light years. Neutrino astronomy, because of the tremendous penetrating power of the neutrino, will extend that range by ten, a hundred, perhaps even a thousand times.

The density of neutrinos in space is probably comparable with the density of all other matter, so that it is now impossible to develop the science of space or cosmogony, without the neutrino. For periods are inevitable in the life of stars when their neutrino radiation even exceeds their ordinary stellar luminosity in amount.

Not so long ago the existence of the neutrino was quite impressively demonstrated. Scientists running experiments in an underground neutrino laboratory three kilometres deep in an old mine near Johannesburg, in South Africa, succeeded for the first time in recording seven neutrinos that arose during interaction of primary cosmic rays with atoms of the Earth's atmosphere.



Chapter Fourteen

THE LATEST ON NUCLEAR STRUCTURE

What is a Nuclear 'Model'?

The bombardment of an atom with alpha-particles carried out by Rutherford made it possible to show that the atom was really empty, since almost all its matter was concentrated in the nucleus, which occupied an infinite small space at the centre.

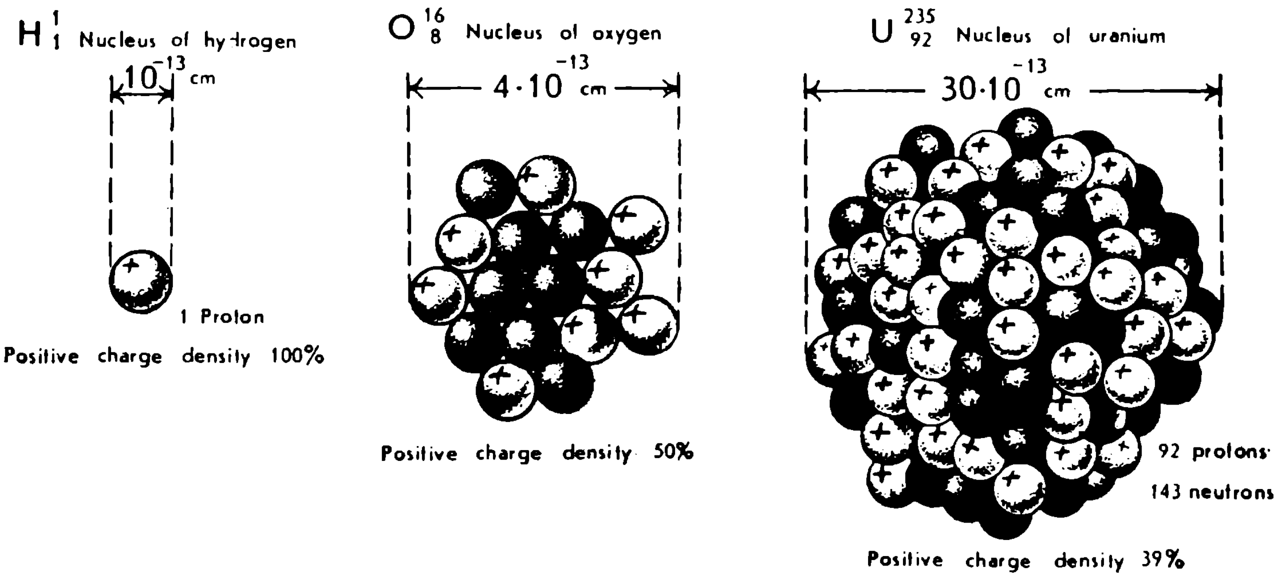
Nevertheless bombardment of the 'empty' atom enabled Rutherford to discover the nucleus in its boundless space and to make a first approximation of the relative dimensions of the atom and its nucleus.

From then on the direction of scientific experiments mainly took that of bombardment of the atom and nucleus, with the aim of knocking some particle out of them, or with any luck to smash the atom completely.

Improvement of the 'atomic artillery' and the fact that atoms and their nuclei quite deftly reflected the most of the particles fired at them, scattering them in various directions, prompted scientists more and more to return to Rutherford's initial experiment, but now not so much to smash the atom, as, so to say, to feel it out, to measure it, and if possible, to penetrate deeper into the nucleus than had been done by earlier investigators. In this connection they were forced to modify some of their previous ideas about the nature of the nucleus and of its constituent particles.

Because all our knowledge of the atom and the nucleus is based on very indirect methods of research, terms like the 'structure' of the nucleus and its 'representation', 'looking into' the atom, and other similar expressions are fictions quite far removed from their direct meaning. The atomic nucleus remains absolutely and irrevocably invisible.

Physicists usually, when referring to the structure of the atom or nucleus, speak of its 'model'. This term more accurately



The charge density of an atomic nucleus depends on the atomic weight of the element, since the volume of a nucleus includes an ever increasing number of uncharged neutrons in addition to charged particles (protons)

reflects our actual knowledge and conceptions of the mysterious, invisible body, that has become the life purpose and object of generation of physicists to study. By careful analysing the results of various experiments physicists are able to develop various theories and construct various models of the structure of the atomic nucleus.

Until recently the liquid-drop model that we considered in some detail in Chapter XIII served as the model of the structure of the nucleus. In accordance with it the density of nuclear matter was taken to be constant, and it was believed that each nucleus had a distinct boundary surface. The larger a drop of liquid is, the more molecules it contains, and by analogy the larger a nucleus, the more nucleons it contains.

Hence a quite simple law can be arrived at that defines the relative dimensions of the nuclei of various elements, namely that nuclear volumes are directly proportional to the number of nucleons in them.

And since both a liquid drop and a nucleus are spherical in shape, their volume is proportional to the cube of their radius. Hence, the radii of various nuclei will vary in proportion to the cube root of the number of nucleons in them. For example, if a large atomic nucleus contains eight times as many nucleons as a small one, the radius of the larger nucleus should be twice that of the smaller one.

For that reason, the size of a nucleus is usually determined in physics by its radius and not by its diameter.

From these considerations, the radius of a nucleus measured in the nuclear units known as fermi (one fermi $= 10^{-13}$ cm), is

$$1.45 \sqrt[3]{\text{the number of nucleons in nucleus}},$$

i.e. the cube root of the number of its nucleons multiplied by a constant equal to 1.45.

From this formula, the radius of the nucleus of gold, for example, which con-

tains 197 nucleons is

$$1.45\ \sqrt[3]{197} = 8.45 \text{ fermi or nuclear units} = 8.4510 \times 10^{-13} \text{ cm.}$$

The atomic nucleus as we know, is positively charged. The uncharged neutrons, of course, do not increase its total charge but do increase its mass.

In comparing an atomic nucleus with a spherical drop of liquid, one must assume that its electric charge is also uniformly distributed over its entire volume.

But here discrepancies immediately appear.

It turns out that the density of the electric charge concentrated in a nucleus of given volume cannot be identical for the atoms of the various elements since it depends on the ratio of the number of protons to the total number of nucleons in the nucleus.

It follows that charge density will be highest in the hydrogen nucleus, which consists of one proton only and contains no neutrons. But when a nucleus contains an equal number of protons and neutrons, its charge density becomes equal to half that of the hydrogen nucleus. And finally in the heaviest nuclei, in which the number of protons amounts to only 39 per cent of the total number of nucleons, charge densities are lowest.

Such a gradual drop in charge density somehow does not tie up with the discreteness (discontinuity, intermittency) of the structure of matter and with its properties in the microworld.

And although the liquid-drop model of the nucleus is often very convenient for explaining many important nuclear properties and correctly reflects certain regularities of its structure, this variation in charge density does not apparently conform with the true state of affairs; consequently, the atomic nucleus cannot be exactly like a drop of liquid.

It is doubtful, for example, that the surface of a nucleus is as distinct as that of a drop of liquid, that is to say its maximum density, distributed uniformly over the whole spherical volume, falls abruptly to zero at the boundary of the nucleus.

Contemporary quantum theory indicates that near the surface layer the density of nuclear matter should gradually fall from a constant value to zero.

In consequence of these contradictions several new theories and models of the structure of the nucleus have been advanced in recent years. According to one of them, the nucleus is a sphere with a very diffuse outline, in which the density of nuclear matter falls uniformly from the centre to the surface. According to another theory, the mass and charge are concentrated in the form of concentric shells. There are other nuclear models as well, differing in the way that density and charge are distributed over the atomic cross-section.

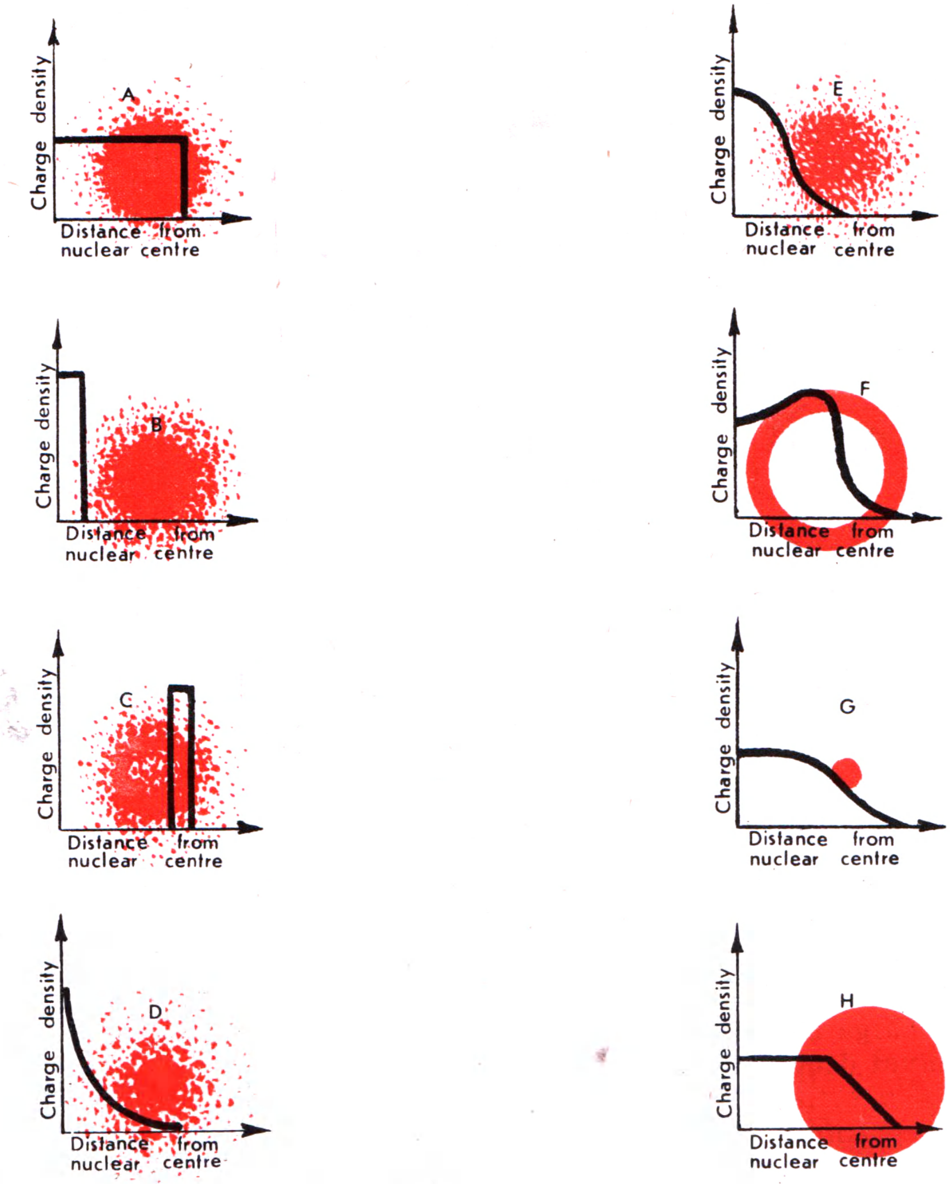
When is a Light Projectile Better Than a Heavy One?

In returning again to Rutherford's early experiments that have made it possible, through the scattering of alpha-particles, to detect the existence of a tiny nucleus in the relatively wide spaces of the atom scientists also recalled the fact that the faster a particle moved, the shorter its corresponding wavelength proved to be. And of all the particles, the ones that can be accelerated most of all, to a velocity approaching that of light, are electrons.

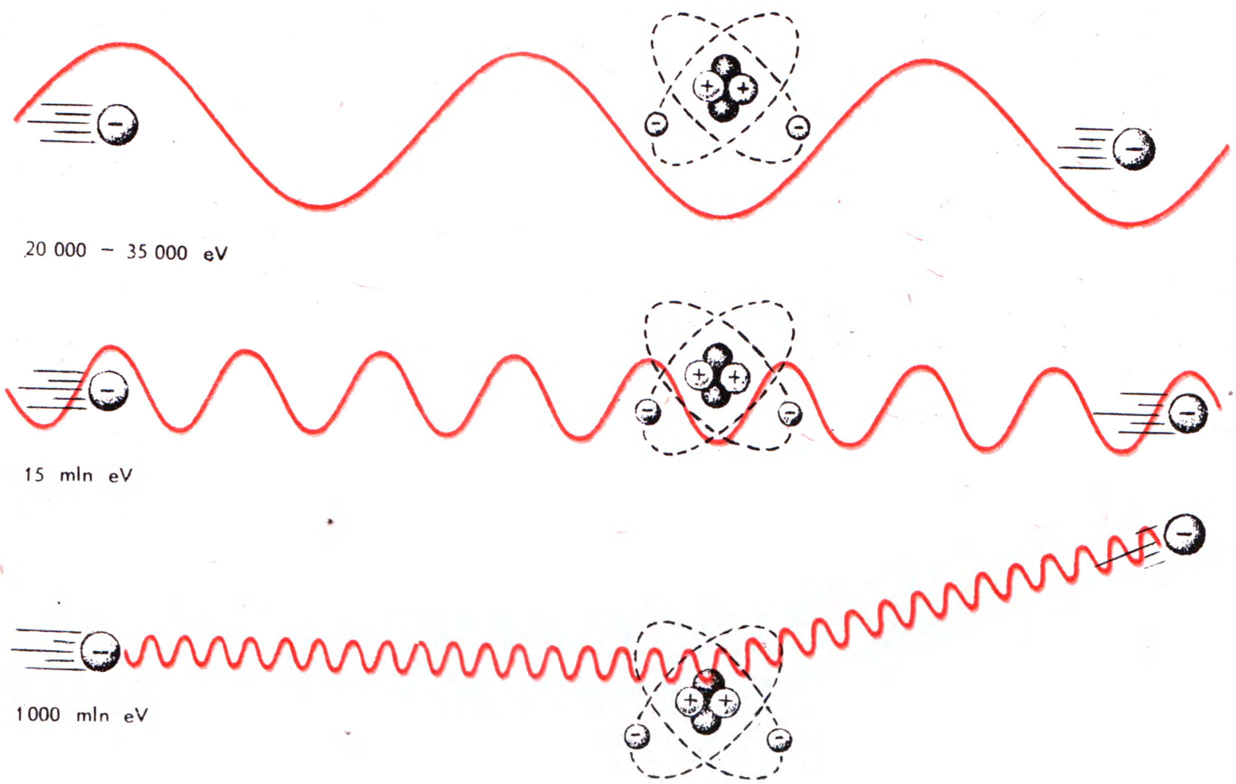
However, only since powerful particle accelerators have been built has it become possible to experiment seriously to determine the size of the atomic nucleus and its constituent particles by the manner in which they scatter high-velocity electrons.

As regards size, electrons are the par-

NUCLEAR MODELS



The structure of the atomic nucleus can be represented by the various models illustrated here. The curve alongside each model shows how the charge density of the nucleus varies with distance from its centre. *A*—the liquid-drop model with a constant charge density over the entire volume of the nucleus, and a sharply defined boundary surface; *B*—the point-like model; *C*—the shell model; *D*, *E*, *F*—models in which the shell varies according to different laws; *G* and *H*—models that give the best agreement with experimental results



The wavelength of an electron moving with a velocity corresponding to an energy of tens of thousands of electron-volts can only be compared with the diameter of the electron shell of an atom. With an energy around 15 million electron-volts its wavelength makes it possible for an electron to penetrate inside an atom. And with an energy of 1 000 MeV its wavelength enables an electron to probe each nuclear particle

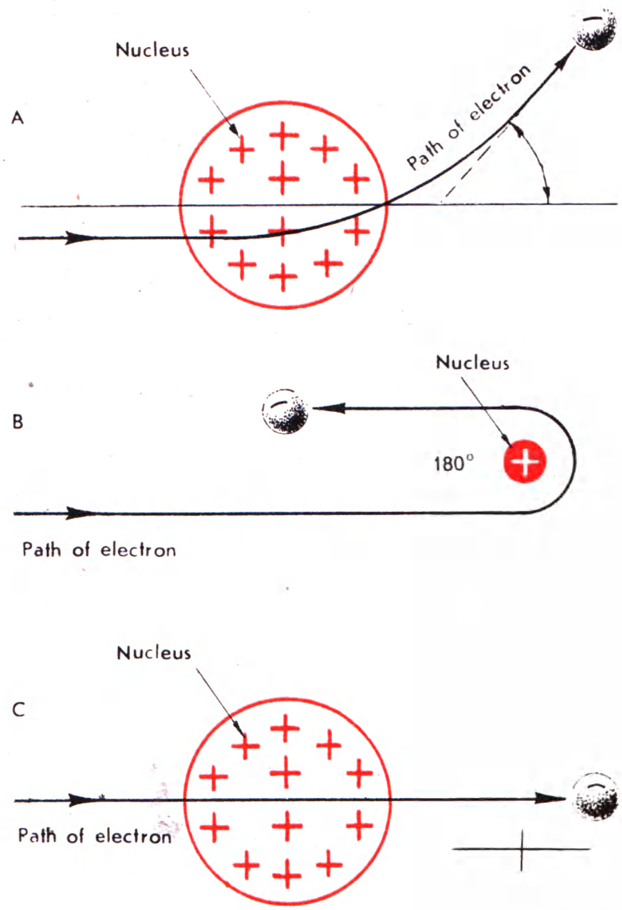
ticles most suitable for this purpose, but it is not only the size of the particle, unfortunately, that is important. Let us take an example.

If the electrons used possess an energy of only a score or so of kiloelectron-volts (KeV) the wavelength corresponding to that energy will be about 10^{-8} centimetre or 100 000 nuclear units (fermi), that is commensurable only with the diameter of the electron shell of the atom. So a beam of electrons, possessing at once the properties of particles and of a wave, would not be able, with such a wavelength, to penetrate an atom, just as, in an optical microscope, it is impossible to observe particles that are smaller than the wavelength of the light illuminating them.

The wavelength of an electron, moving with an energy around 15 MeV, is hundreds of times shorter, and such a wave is already capable of penetrating inside the electron shell of an atom and feeling out the nucleus, but is still not able to detect its constituent particles.

In 1951 a powerful accelerator was built that gave a flux of electrons with an energy of 600 MeV. Its wavelength was only a few fermi (nuclear units), which proved short enough to identify and differentiate the particles from which nuclei are composed.

As a 'nuclear probe' the electron has another advantage. Not being a nucleon, the mysterious intranuclear forces do not affect it. Once inside the sphere of action of the protons or neutrons of the



How a high-velocity electron will interact with a positively charged atomic nucleus: *A*—the electron flies through the field of force of a diffuse atomic nucleus at its periphery, with the result that its path is deflected; *B*—the electron passes in close proximity to a point-like nucleus, in consequence of which it may even turn back; *C*—when a very fast electron hits a diffuse nucleus it passes right through it and is not deflected

nucleus, electrons are only affected by electrical or magnetic forces that are quite well known and can be accurately measured and calculated.

Regularities of Electron Showers

When a high-velocity charged particle, in this case an electron, passes through the electric field of force created by an atomic nucleus, it is naturally deflected from its initial direction. But whenever an electron enters an atomic nucleus, cuts into as it were, it is more convenient to consider the resulting events from the wave properties of the electron, i.e. to take its diffraction into account rather than its deflection.

The process of reflection itself, or rather of scattering, will depend to a considerable extent on the nature of the nucleus bombarded.

When it is a matter of a very small, dense material point or ball, the closer the bombarding electron comes to the centre of the target, the greater its angle of deflection will be. Electrons that fly too close to the nucleus may be attracted to it so strongly that, on rounding the nucleus they fly back, i.e. their angle of deflection proves to be 180°.

Now, let us assume that the atomic nucleus has diffuse structure of some sort. Electrons will behave and be scattered in quite another way. An electron flying at high speed into the very centre of such a nucleus, will find itself surrounded with a positive charge of equal magnitude, consequently, it would have 'nowhere' to turn, since it would be attracted from all sides by the positive charge. It would therefore pass right through such a nucleus, without being deflected from its initial path.

Hence, an investigator is faced with a relatively simple problem to begin with. If the nucleus is a small but very dense body, a 'point', then, when it is bombar-

ded with fast electrons, a tremendous number of the latter can be expected to scatter at large angles up to 180°. But if the nucleus is diffuse in structure, the number of electrons so scattered will be relatively small.

The general picture of the scattering of electrons by a diffuse nucleus will be similar to that of the diffraction of light as it passes through a small aperture or a narrow slit. For you will remember that particles moving at high velocities simultaneously display the properties of particles and waves. The screen on which light falls after passing through a very small aperture produces a bright spot surrounded by dark and light rings, which become weaker and weaker the further they are from the centre. Electrons will be scattered in roughly the same manner, depending on their angle of deflection from their original path. From the distance between the light rings it is possible to calculate the diameter of the aperture through which the beam of light has passed quite exactly. Similarly it is possible to estimate the size of a nucleus by measuring the distance between the maximum scattering of the electrons diffracted by it.

Small-Calibre Atomic 'Artillery'

The linear electron accelerator of Stanford University that was used for experiments of this kind accelerates electrons to energies of 1 000 MeV, but in clusters of electrons, about 60 volleys per second rather than in a continuous flux. Each volley lasts a millionth of a second and contains 10 000 million (10^{10}) electrons. A powerful magnet bends this flux so that a very thin beam of electrons of equal energy enters a narrow slit, but not those of greater or lower energy. Having passed through the slit the electron beam is directed onto a target, e.g. a very thin gold foil.

At first glance, it might seem that it is sufficient in order to determine the picture of how electrons are scattered by nucleons to place instruments around the foil to catch them and count the number reflected at different angles. The bombarding installation would then have been much simpler than it actually was, in particular, there would have been no need for another large horseshoe-shaped magnet, weighing 45 tons, which, by bending the flux of electrons already reflected from the target, grades them quite accurately according to their energy. But this bending of the flux is very important and, consequently, necessary. Simple counting of the electrons deflected at different angles is quite insufficient.

The fact is that not all particles fired into an atomic nucleus interact with it, so that the angle of deflection of particles after their encounter with a nucleus does not always give a true picture of the latter's structure. Everything depends on the energy level of each of the bombarding particles. In some encounters the electron and nucleus may behave like two billiard balls colliding and rebounding from each other, or rather, the behaviour of a light celluloid table tennis ball colliding with a cannon-ball, for the total energy of motion (kinetic energy) of the colliding particles does not change. The phenomenon is known as elastic collision.

The larger particle, the atomic nucleus, being many times heavier than the electron, is deflected only slightly by such a collision, while the electron sharply changes direction but preserves almost the same energy that it had before the collision.

The collision may also happen in such a way that the electron loses an appreciable part of its energy, which is expended on additional excitation of the nucleus, that is, on increasing the level

of its internal energy, which will manifest itself in more vigorous and faster movement of its nucleons. But this kind of collision is inelastic.

Now if electrons from the two types of collision are mixed together, the results obtained will be incorrect and distorted.

It is quite obvious that the atomic nucleus should be investigated in its normal unexcited state in order to get a true picture of events. For that purpose it is necessary to select only the electrons that have preserved their energy as a result of elastic collisions.

The Stanford accelerator has a device for counting the electrons that hit the target, since it is impossible to draw trustworthy conclusions if one knows only the number of electrons deflected at various angles, and has no idea of the total number hitting the target.

Notwithstanding the exceptionally important results obtained by means of a linear accelerator that produces electrons of energies up to 1 000 MeV, which enable the structure of the nucleus and the nucleon to be probed, such energies proved insufficient. To investigate the structure of nucleons, the wavelength of an electron of that energy, calculated by the de Broglie formula, proves not to be short enough. And after the nucleons, it is necessary to investigate the structure of mesons and of other still finer particles including the most important and still puzzling particle of the lot, the electron itself.

On the basis of these considerations and many others, a linear accelerator was commissioned in 1963 at the Applied Physics Institute, near Kharkov, producing electrons of an energy 2 000 million electron-volts (2.0 GeV), designed especially to investigate the structure of protons and neutrons.

The 'barrel' of this peaceful gun, a copper waveguide in which electrons are accelerated, is 240 metres long, and consists of 50 sections, in each of which a bunch or cluster of electrons, injected 50 times a second, is accelerated successively by electromagnetic pulses of 20 megawatts until they acquire an energy at the end of the tube of 2 000 million electron-volts (2.0 GeV)!

But why do scientists use both in the USA and the Soviet Union linear accelerators, and not accelerators of other types to produce high-energy electrons?

The point is that a charged particle, not being in linear motion but moving in a spiral orbit, emits electromagnetic waves after a certain energy has been imparted to it. The energy lost in the emission of these electromagnetic waves is inversely proportional to the square of the mass of the particle. It turns out that the lighter electron, moving in an orbit of the same radius as the more massive proton, loses four million times more energy. And this law of nature can only be got around by increasing the radius of the electron's orbit, i.e. by straightening its path to the ideal, a straight line.

New Discoveries, New Models

Long-time experimental studies and subsequent complicated mathematical analysis clearly showed that the former nuclear models needed serious correction and alteration, or rather it became clear that new nuclear models should be constructed. Naturally, these new models are probably still not exact, and in a number of details simply erroneous, but they reflect the actual structure of the nucleus better than earlier ones.

According to one of those models the nucleus of gold, for example, has a dense core that extends four nuclear units from the centre, then loses density rapidly and disappears at a distance around nine nuclear units.

The creation of this new model without distinct boundaries has resulted in it being difficult to determine where exactly it begins or ends, what should be considered its boundary, and so on.

If we take the thickness of the transition shell of the nucleus of gold as the distance from the point where the charge density is 90 per cent of the maximum to the point where it drops to 10 per cent, the thickness of this arbitrary transition will be about 2.4 nuclear units. If we determine the size of a nucleus as the distance from its centre to the point where its density is 50 per cent of the maximum, we obtain an average around 6.3 nuclear units.

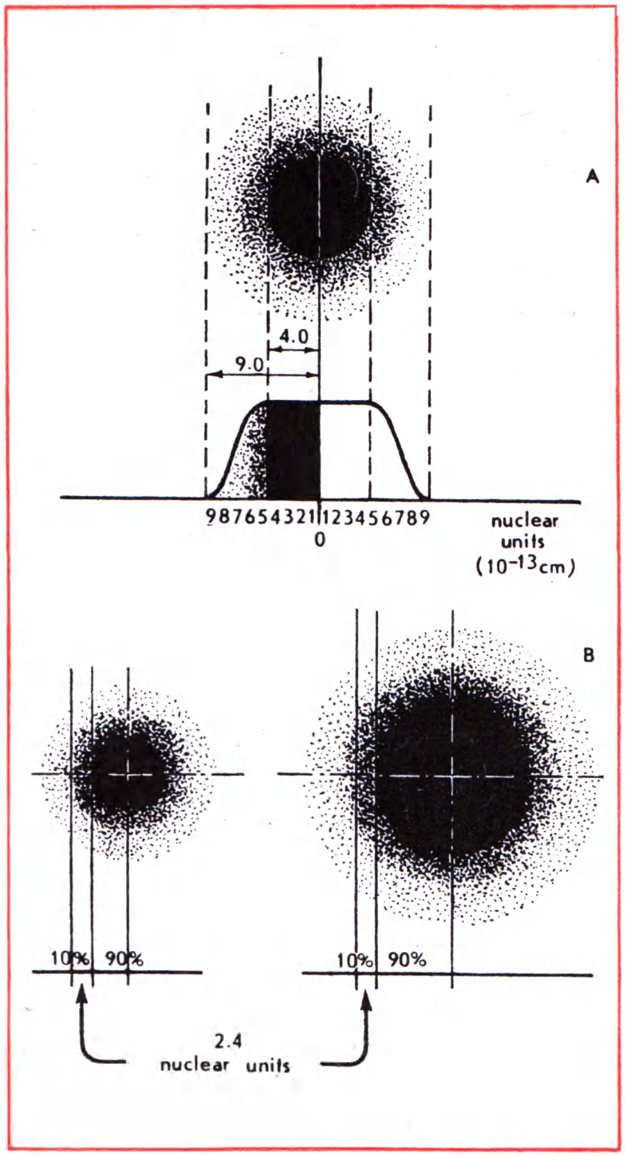
For nuclei with an atomic number over 40, a curious regularity is observed. For all of them without exception the thickness of the transition shell proves to be amazingly constant and also equal to 2.4 nuclear units. The size of the dense nuclear core varies, naturally, according to the number of nucleons, but the thickness of the diffuse external shell remains the same.

Experiments with nuclei of an atomic number under 40 have shown that they have no inner core, and that their density diminishes from the centre to the periphery.

Can We See Atoms?

In several places in our book we have already said that the world of microparticles is so small that men are unlikely, either in the future or at least very soon, to succeed in observing an atom directly, or the particles of which its nucleus is built, instead of indirect signs of its existence (tracks in cloud chambers, spark and bubble chambers, or the stacks of nuclear emulsion, etc.). But as far as the atom is concerned, our assertion is no longer correct.

The advances in electronics and electron optics of recent years have led to



Conclusions drawn from bombarding nuclei with superfast electrons: *A*—the nucleus of gold has a dense core, extending four nuclear units from the nuclear centre, then diminishing rapidly in density to nothing at a distance around 9.0 nuclear units; *B*—the thickness of the transition shell of the nuclei of atoms with an atomic number greater than 40 proved to be constant at 2.4 nuclear units irrespective of the diameter of the nuclear core. The nuclei of atoms with an atomic number under 40 have no core; their nuclear density gradually diminishes from the centre to the periphery

the creation of a whole series of instruments, electron microscopes, that enable pictures to be taken with a magnification of 400 000 to 500 000. With them it has been possible for the first time to see on these plates viruses, whose dimensions are hundreds of times less than those of the bacteria observed under ordinary optical microscopes.

Scientists have succeeded even in observing the individual giant molecules characteristic of certain plastics and rubber.

But even the most perfect electron microscope does not allow particles smaller than ten Angstrom units to be observed (an Angtsrom unit is equal to 10^{-8} cm).

Some time ago Dr. Ervin Muller, professor of physics at the University of Pennsylvania, in the USA, succeeded for the first time in taking pictures of individual atoms by means of what is called an ion field-emission microscope, which gives an image magnification of five million or more, i.e. a magnification 20 to 40 times greater than that of an electron microscope.

We are not in a position to go into the fundamentals of electron wave optics here even briefly. We can only mention that it is impossible to extend the maximum magnification of the ordinary optical microscope (1 500-2 000) because the light waves are not reflected from an encountered object if the diameter of the latter is shorter than their length. The light, then, simply passes round the obstacle. In optics this phenomenon is referred to as the diffraction of light. It can be overcome solely by using light of a shorter wavelength, by illuminating an object invisible to the human eye with ultraviolet rays, for instance, and photographing it on plates sensitive to these rays.

Rays shorter than those of light, electromagnetic oscillations or X-rays, cannot be used in a microscope. Their wave length is so short that no materials or practical methods exist enabling them to be reflected and focused, i.e. for the appropriate lenses.

These difficulties led to the creation of the electron microscope. Even a bundle of electrons accelerated to high velocities can be bent relatively easily, gathered together, and scattered by means of electric and magnetic lenses.

From physics we know that a fast moving particle, an electron in this case, also possesses wave properties; and the length of the wave is the shorter, the higher the velocity of the moving particle or the greater its mass.

Unfortunately it is very difficult to design an electron microscope working at a voltage above 100 000 volts, the mass of the electron being extremely small. Taking all that into account, it is possible to put off considerably the moment when harmful diffraction sets in (compared with the optical microscope), but the image obtained is still 'only' magnified 5 000 to 10 000 times. The magnification can be increased further by a factor of ten or twenty by purely photographic means, so that a total magnification of 400 000 to 500 000 is obtained.

The drawbacks of the electron microscope suggested to scientists the idea of replacing the too light electron by a heavier proton or by a positively charged ion of heavy hydrogen or even helium.

Such an ion, with a mass several thousand times greater than an electron, and accelerated to high velocity and, consequently, energy, has more favourable wave properties; its wavelength proves to be much shorter than that of the electron, and that postpones the moment of diffraction sufficiently to make it possible for the proton to be reflected from particles comparable in size to an atom.

The instrument developed by Prof.

E. Muller consists of a flask with double or triple walls, the spaces between them being filled with liquid nitrogen or hydrogen. In external appearance the flask resembles a television tube. Its bottom is coated with a luminescent compound forming a screen and an electrode ending in a very fine tungsten needle is positioned at the centre of the flask, with the tip of the needle facing the screen. A high electric potential around 30 000 volts is applied between the needle and screen, and this potential, because of the small radius of the needle tip, creates a voltage on the screen of 500 million volts per square centimetre.

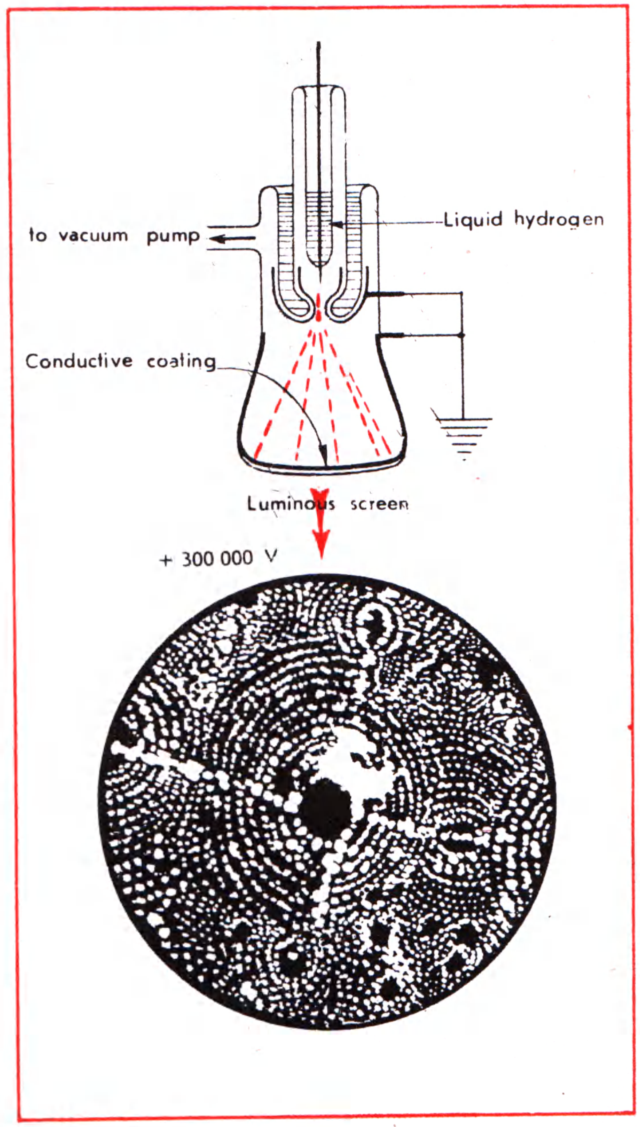
Air is evacuated from the flask, and then a small amount of helium gas is introduced.

How does this microscope work?

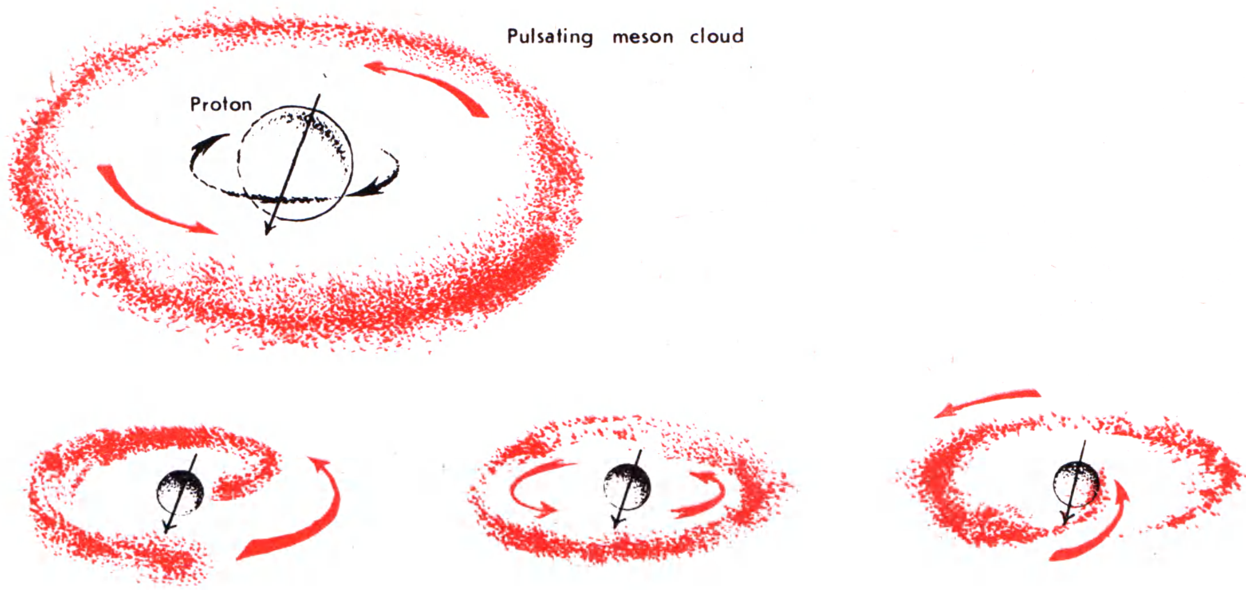
When an atom of helium comes very close to the tip of the needle (as though in contact with it), the tremendous positive voltage applied to the needle knocks an electron out of the 'careless' atom.

The positive helium ion thus formed at the tip of the needle, being attracted by the negative charge of the screen and driven away as strongly by the repulsing positive charge of the needle, is instantaneously accelerated to tremendous velocity, and on hitting the screen, makes it brightly luminescent.

Tungsten has a stepped crystalline structure, and the strongest electric field forms near each protrusion of such a step. And at these points hundreds of thousands of helium atoms are 'stripped' simultaneously, which then rush in a diverging beam toward the screen, where they form an image, reproducing exactly the stepped structure of the surface of the needle magnified two million times, the degree of magnification being equal to the ratio between the area of the needle and that of the screen. Each light point on the image obtained will



Muller's ion field emission microscope, which permits observation of individual atoms



The proton proved to resemble the planet Saturn. For part of its life the particle is surrounded by a sort of ring, a meson cloud that appears and disappears

correspond to the location of an atom in the crystal lattice of tungsten.

The need to cool the tip of the needle with liquid hydrogen arises from the following delicate circumstance. Not all the helium atoms, you see, are ionized as they come close to the tip of the needle. At ordinary temperatures many of them move with velocities so high that they recoil from it in all directions. But if, in doing so, they should nevertheless become ionized, their flight to the screen and the ensuing luminescence of the latter will no longer correspond to the picture of the section of the needle surface, near which the helium was ionized. So the general picture of the arrangement of atoms in the crystal would be strongly distorted.

But when the surface of the point is cooled to the temperature of liquid hydrogen (—252°C), the kinetic energy of the helium atoms falls sharply near it and as they lose their kinetic energy, they stick as it were to the atoms of the material of the needle and on rebounding from them, do not too quietly enter the zone where they will be ionized.

The drawing on p. 253 illustrates the layer of tungsten atoms located at the very tip of the needle. Each point of light represents a tungsten atom, the diameter of which is a little bigger than one hundred millionth of a centimetre (one ten thousandths of a micron).

How They Peeped Inside a Proton

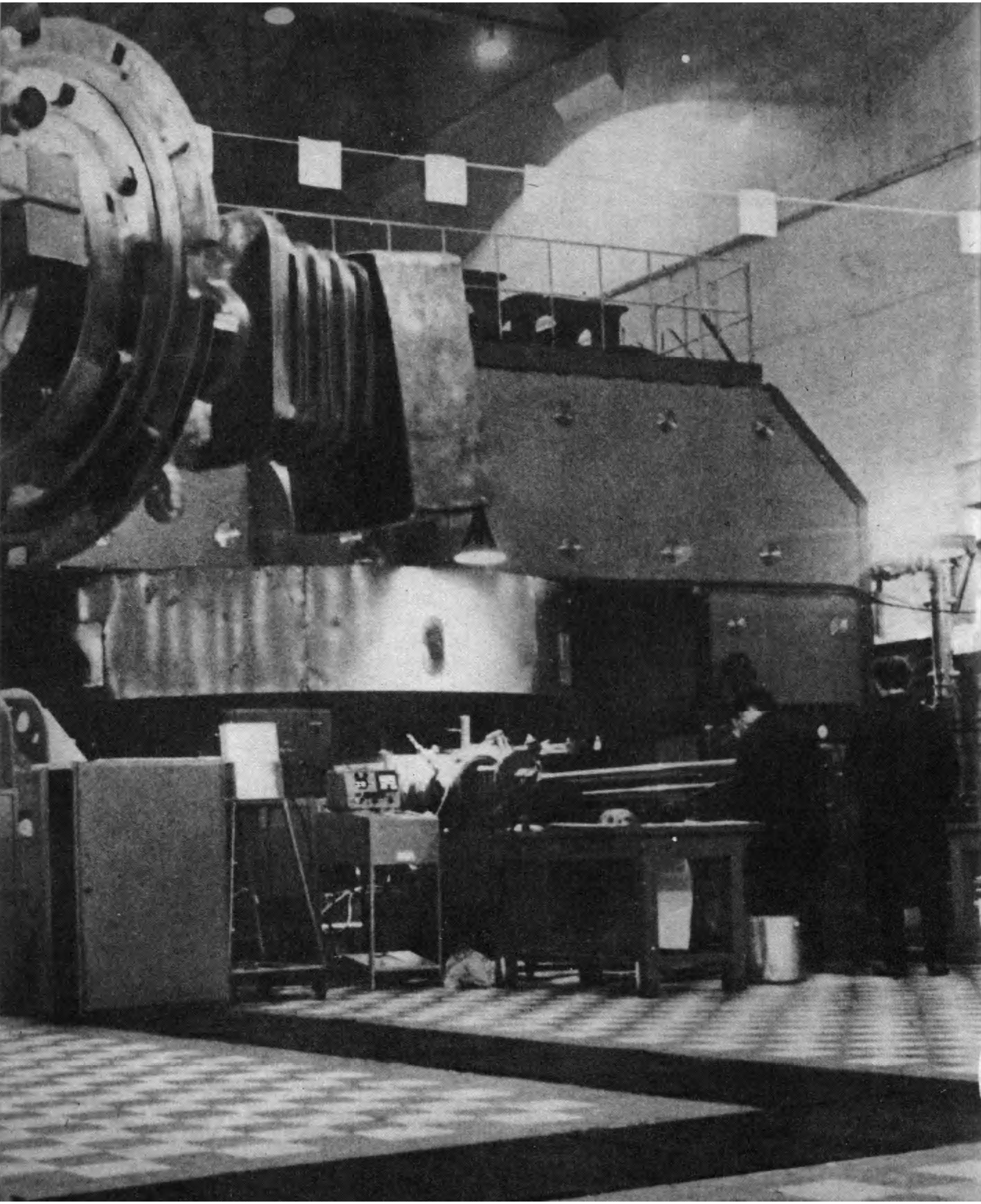
The successful 'probing' of atomic nuclei inspired scientists to find out, if only approximately, the nature of the atomic nucleus that is at the same time an elementary particle, i.e. the proton. With that end in view the nuclei of hydrogen gas were bombarded with electrons.

It was found that the proton is also some kind of extended body, whose charge density drops from maximum to zero over a distance of 1.4 nuclear units from its centre.

But according to available data, the proton is a 'stripped' nucleon, periodi-

cally giving off a cloud of pi-mesons that rotates around it during an incredibly short time, and is then pulled back into it. When the proton is bombarded with electrons, the latter are most likely reflected from this meson cloud and not from the core of the proton itself.

Such discoveries made the picture of the structure of the atomic nucleus and its constituent particles more and more complicated. It may be that these intricacies conceal very simple things and that the still fragmentary data, obtained by scientists by means of new research methods, are spontaneous, temporary transitions of intranuclear particles from one relatively simple state to another, no more complicated state. But when they are snatched in fragments 'out of the air', these transitions create a very complicated picture.



Chapter Fifteen

COMPETITION WITH SPACE

Cosmic Rays

Following the discovery of X-rays in 1895 and of radioactivity soon after, it was naturally asked whether there were other, yet unknown radiations in nature that would reveal other, still concealed physical processes taking place in the depths of matter.

And indeed reports of new discoveries, one more sensational than the other, presently began to appear as if from a horn of plenty. But they all either concerned already known phenomena, concealed by some still little investigated features, or were the result of honest mistakes made in experiments. And a few, fortunately only a few, were 'discoveries' that proved to be fruits of unscrupulous pursuit of fame.

One phenomenon remained extremely suspicious for a long time, and did not lend itself to normal scientific explanation.

It concerned the ordinary electroscope used in schools the arrangement and principles of which we described at the beginning of the book.

The puzzling point was that whatever measures were done to maintain its electric charge the leaves invariably fell some time after and the charge gradually leaked away.

The phenomenon could be reproduced artificially by exposing the electroscope to X-rays or by putting a piece of radioactive material near it. Then everything was clear. The gas filling the vessel was ionized by the radiation (X-rays or radioactive), and the gas, an ideal dielectric, was turned into a quite good conductor through which the electric charge accumulated on the leaves leaked away into the surroundings. The process was slowed down noticeably by putting the electroscope in a case with thick lead walls. Since the self-discharging electroscopes were not exposed to X-rays or radioactive radiation, scientists could only

suppose that it was effected by some other, still unknown radiation.

And although the electroscope could be protected in some way from X-rays or radioactive radiation (by a layer of lead, water, concrete, etc.) nothing could shield it from this mysterious radiation, even when it was put into a deep mine or at the bottom of a lake.

Thinking that the mysterious radiation was given off by radioactive elements still unknown in Earth's crust, and that its intensity would naturally decrease with the height, the German physicist W. Hess began in 1912 to launch balloons carrying recording apparatus to a height of 5 000 metres. To the surprise of scientists, the radiation proved to be more intense at high altitude than at the surface. Numerous further experiments demonstrated that the new radiation arrived from some source in outer space, or Cosmos, and so the radiation became called *cosmic rays*.

For thousands of millions of years a stream of cosmic rays has poured onto our planet without a second's pause, sometimes as separate bursts and sometimes in dense showers, penetrating every thing, living or dead, with colossal velocity.

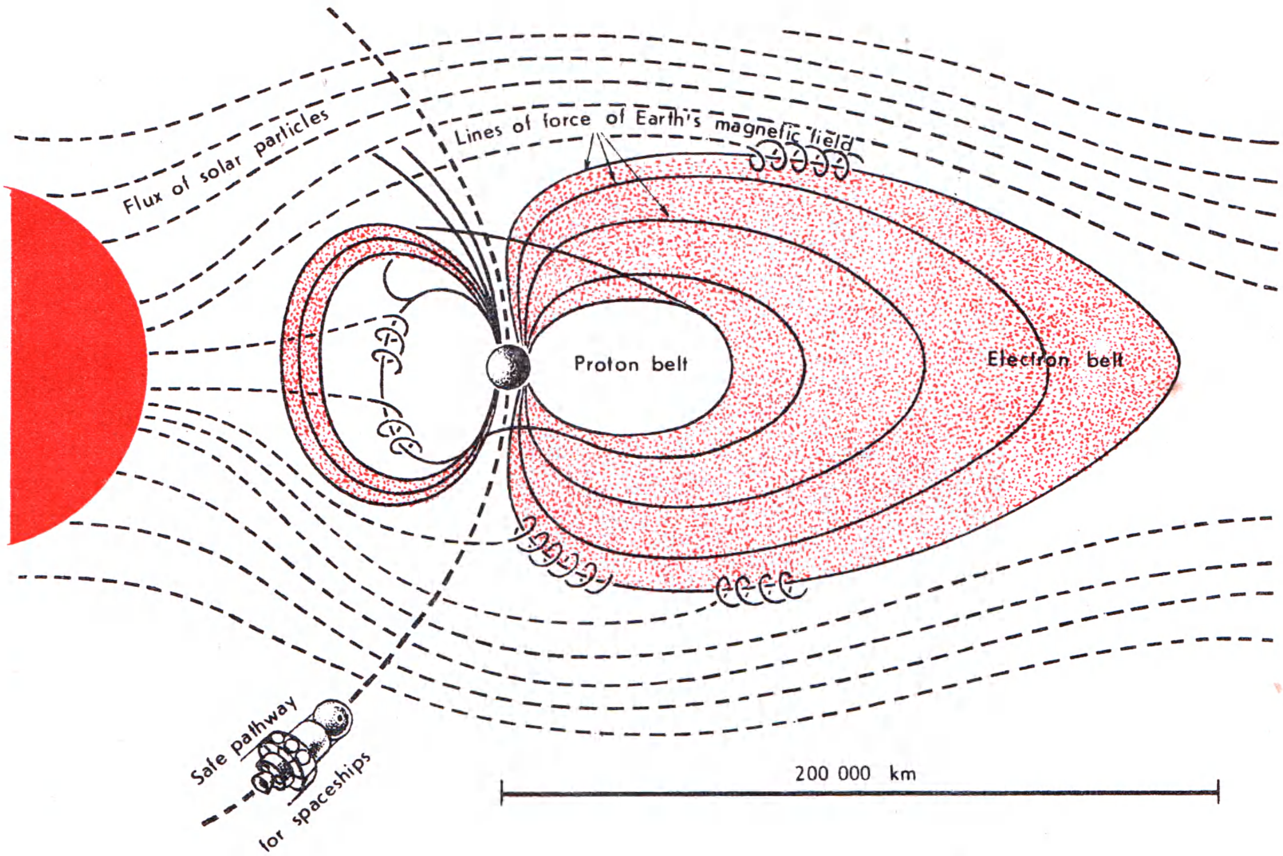
The very first attempts to determine their nature brought many surprises and revelations. To begin with, they happened not to be rays but particles, differing greatly in charge, mass, and energy; most were protons (hydrogen nuclei), a small number were alpha-particles (helium nuclei) and quite rarely, the nuclei of heavier elements still, carbon, nitrogen, iron, etc. Later it was found that most of these particles possessed tremendous energy, some even fabulous levels of a million million million eV (1 000 million GeV), whereas the fastest and most penetrating particles emitted during radioactive disintegration 'barely' reached an energy of ten million electron-volts (10 MeV).

Cosmic particles were recorded even at depths of several thousand metres underground or under water. And finally, what is most important, experimenters established that the rays reaching the Earth did not contain any genuinely 'cosmic' particles. The overwhelming majority of these new 'rays' were the countless fragments of nuclei of the air smashed to smithereens by a head-on collision with a genuine primary cosmic particle, possessing such tremendous energy that fragments turned into rays of almost the same cosmic energy, capable just as easily of splitting other nuclei of the atoms of the air. Even the 'fragments' of the fragments of several generations of smashed nuclei could create an avalanche growing like a snowball, a peculiar chain reaction of nuclear disasters. And not only fragments. The tremendous energy released during these collisions gives rise to whole families of new, short-lived particles that do not exist in ordinary conditions and which, on disintegrating, produced new particles possessing the most diverse physical properties and characteristics. It was as if Nature created her own 'artificial particles' one thousand millionth of a second, thereby inadvertently unveiling the most deeply hidden secrets of the formation of matter.

It is almost impossible to separate out from this stream the perpetrators of the initial disasters.

Being exposed to such continuous bombardment by cosmic particles, living matter has become adapted to some extent to it in the course of evolution, and has developed measures of protection; and the process of adaptation is undoubtedly still going on.

It would have turned out badly for mankind, if the vast flux of particles itself were not in fact relatively sparse; only around 250 particles fall per second on each square metre of the earth's sur-



Earth's magnetic field is a kind of an armour protecting it from a flux of superfast charged particles. Through the action of the stream of particles radiated by the Sun, Earth's magnetic field is considerably flattened on the illuminated side

face. Therefore, scientists consider the ordinary doses of this radiation passing through our special protective armour, the atmosphere, to be harmless to the human organism. And we do not notice the effect of these particles, and do not know how life would have developed on Earth if this radiation had not existed.

But the effect of the primary rays on the cells of living organisms can prove to be quite different, as men more and more often leave the saving armour of our planet, its atmosphere and magnetic field, for longer and longer periods. And no wonder that the mysterious leakage of charges from the school electroscope gave impulse to the birth of a very big branch of modern physics, the physics of cosmic rays and then the physics of elementary particles, which have now become some of the most important sectors of the far-flung borders of science.

Now there is no longer any doubt that cosmic rays are a complicated natural phenomenon in which nuclear processes play the main role, and in which, in addition to the known atomic particles (protons, neutrons, and electrons), new, quite unusual particles appear, not previously observed in nature and possessing even more amazing properties.

On colliding for the first time with the nuclei of atoms of the air of the atmosphere, and smashing them, primary cosmic rays expend only a small fraction of their initial energy. But even that amount is sufficient to initiate a long chain of complicated transformations of particles into other ones, until the unex-

pended remaining energy is insufficient to give rise to any more.

The first particles to be produced are mainly charged and neutral pi-mesons, which disintegrate at once and give birth to mu-mesons, which possess tremendous penetrating power. Strictly speaking, it is these particles that are taken to be cosmic rays, although they are of a purely terrestrial origin; suffice it to say that it is they that are capable of penetrating layers of rock and water thousands of metres thick.

But some pi-mesons, especially those of large energy, do not have time to disintegrate. They cause the formation of extensive secondary atmospheric showers. Neutral pi-mesons disintegrate very rapidly, and each of them forms two high-energy photons. Each of these photons gives birth to a pair of particles, an electron and a positron, which annihilate (destroy) each other and form photons of smaller energy. All these successive and parallel nuclear interactions result in a powerful shower of particles falling on the earth's surface, namely, protons, neutrons, and pi-mesons, giving rise in their further development to a host of electrons, positrons, and photons.

Only the vast amount of data and research findings accumulated enabled scientists to bring some order into this chaos of particles, classify them according to energy, mass, and charge, and to trace their genaeology more or less exactly. Very complicated apparatus, consisting of thousands of separate particle counters, hundreds of ionization chambers, a great many photomultipliers, cloud chambers, and so on was employed for this purpose. You may well ask where the particles comprising the initial cosmic rays come from. Where, and under what circumstances, are they accelerated to these truly fantastic energies, reaching tens and hundreds of thousand giga-electron-volts (10^{17}-10^{20})?

No one has now doubts that so tremendous an energy could only be imparted to particles by the electromagnetic forces created by the very rapidly expanding envelopes of what are called novae and supernovae, i.e. disastrous cosmic explosions, or as a result of even more powerful natural phenomena, the mysterious explosions of the central nuclei of galaxies. The mass of plasma ejected then is not just some fraction of a single star, even a gigantic one, but the mass of scores, and possibly hundreds or thousands of stars. The resulting electromagnetic fields of titanic force are capable of accelerating particles to the maximum observable energies.

Thus, when previously accelerated particles get into such electromagnetic fields they are accelerated still more. And after journeying for a long time through the expanses of our Galaxy, and having undergone innumerable accelerations, decelerations, and changes of direction, the particles become so thoroughly intermixed that they reach Earth uniformly from all sides. It may be that some of the high-energy particles come from other galaxies. The magnetic fields of our Galaxy lack the force to divert them, and they enter and leave it freely, unhindered.

Scientists still cannot foretell whether there are ways that would enable men to make practical use of cosmic rays even in the very distant future. But their investigation puts very powerful weapon into our hands, enabling us to penetrate the most hidden mysteries of nature, to understand the properties of matter that manifest themselves only at highest velocities of particles and least interaction distances between them, and to understand the structure of the microworld within the limits of our Galaxy, the metagalaxy, and the whole Universe.

The logic of the development of science should inevitably lead to a number of

new fundamental discoveries and conclusions enabling us to solve one of the most important problems of current natural science, i.e. the problem of the structure of the smallest elementary particles (protons, neutrons, electrons, mesons, etc.) which the matter around us is built from or may consist of.

There is also another aspect of the problem of cosmic rays and particles. Fluxes and showers—these are terminology of science. For all the grandiose character of these amazing phenomena they are quite rare, or rather, on the scale of the macroworld, sparse, spread over vast space. With all the attraction of investigating the effect of particles possessing an energy of thousands of millions of giga-electron-volts on other particles, scientists have to wait for weeks and months for such a collision to occur. It is not surprising, therefore, that they are impatient and strive to create powerful artificial accelerators that can produce particles not only possessing tremendous, nearly cosmic, energies, not simply singly, but in very intensive fluxes that cannot be observed with cosmic radiation. So far they have succeeded in producing particles with energies only tens of thousands of million electron-volts (10 GeV), but with densities millions of times that of natural radiation. This has made it possible to produce artificially on Earth particles that were previously only detected in cosmic rays. And it is far from the limit. As the technical means and study of natural cosmic rays improve the still immense gap in energies will be gradually overcome.

About 'Electron-Asses', 'Dirac's Sea', Anti-Particles, and Other Obscure Things

The beginning of this story can be traced to 1928, when physicists still believed that all natural substances consisted solely of positively charged particles, protons, and negatively charged particles, electrons. But that year the famous English physicist Paul Dirac attempted to create a theory that would not only explain the structure of electrons, but, drawing on the advances of contemporary theoretical and experimental physics, would simultaneously meet the requirements following from Einstein's theory of relativity.

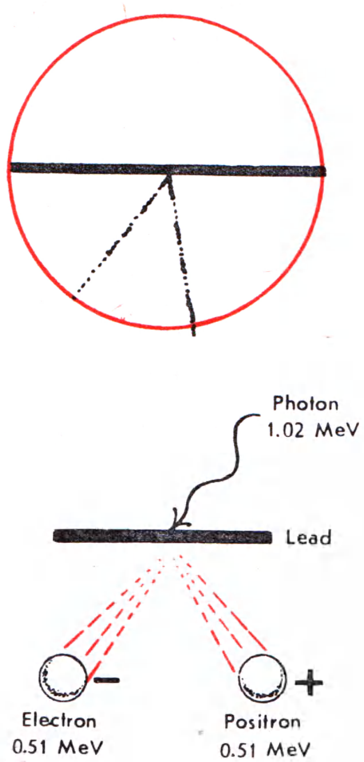
The equation derived by Dirac, defining the spin of an electron about its own axis and the physical properties associated with this spin, agreed very exactly with the experimental data previously obtained, in particular from study of the properties of the lines of the optical spectrum of light.

But an unforeseen circumstance arose at once that confused scientists. For the new theory to be correct there had to be electrons, possessing negative energy and negative mass. The electrical forces affecting such electrons would force them to move in a direction opposite to that of ordinary motion. It is doubtful whether at that time or even now anyone has been able to visualize clearly what negative energy and negative mass mean. Of course, such particles, which soon began to be called 'electron-asses', have never been observed in nature, and their recognition could create the most incredible complications for physics.

So Dirac was forced to look for some way out of the difficulties created.

He suggested that electrons could occupy a negative energy state in certain conditions, and that all of these states, or levels of negative energy in the world around us were occupied by electrons.

In his view, everything that we had hitherto considered to be empty space should be regarded as a continuous and infinitely large number of electrons, in all possible states of negative energy. At the same time their total electromagne-



The appearance and disappearance of a positron and electron (from top to bottom). A photon of cosmic origin (which is invisible because it has no charge) knocks a pair of charged particles, an electron and a positron, from a lead plate placed across a Wilson cloud chamber. The minimum photon energy ($h\nu$) needed to produce a pair of electrons (e^-) and positrons (e^+) is 1.02 MeV or 0.51 MeV per particle. On meeting, the positron and electron annihilate each other (vanish) turning into two quanta of radiation with an energy of 0.51 MeV each

tic and gravitational effect is zero. This mental picture of the continuous multitude of states of electrons with negative energy levels came to be called 'Dirac's sea'.

Any oscillating and continuously changing mass of water includes bubbles, spaces where there is no water. According to Dirac, such a bubble is, as it were, a 'hole' in a continuous 'sea' of electrons with negative energy states, which should, consequently, behave in a way opposite to that of an electron, that is to say, as a particle of positive mass and positive charge.

Moreover, an ordinary electron falling into a 'hole' would inevitably vanish, together with it, emitting a quantum of energy. This process of mutual disappearance of the electron and the 'hole' that seemed to possess the properties of a positive charge in a 'sea' of electrons of negative charge, is called the self-destruction or annihilation of matter.

The First Anti-Particle—the Positron

For some time it seemed that the physical essence of this 'hole' might be identified with the only positively charged particle then known, the proton. But that did not agree in any way with the stability of the hydrogen atom in which the oppositely charged proton and electron can exist inoffensively together infinitely, whereas the rate of annihilation of the electron and 'hole', according to the new theory, should be practically instantaneous.

In addition, the proton is about 1 836 times as heavy as the electron, and it was impossible to understand what would happen to the difference in mass of these two particles as a result of their annihilation and disappearance, all of which, taken together, made Dirac's idea more than questionable.

But in 1932 the discovery of the positron, a positively charged particle with a mass exactly equal to that of the electron at once dispelled all doubt.

The theoretically postulated existence of the 'hole' was fully substantiated by the existence of the positron, a physical reality that differed a little, it is true, from what Dirac had visualized.

Presently scientists succeeded in observing the process of positron-electron annihilation itself, as a result of their collision. The two particles vanished,

emitting two quanta of energy. The probability, repetition rate and speed of the event fully agreed with the theoretical predictions.

Thus, the theory of the electron suggested by Dirac, which had inevitably in the course of checking undergone the changes that are natural for any modern physical theory, was fully and brilliantly confirmed by this discovery. It has found further substantiation in the fact that positrons, previously only identified in cosmic radiation, were soon detected in laboratories by means of very hard gamma-rays that pass through matter in definite conditions. The process occurring then is the complete opposite of annihilation; a certain number of radiation quanta vanish and in their place two kinds of particles, electrons and positrons appear.

The transformation of a gamma-quantum into an electron-positron pair is only possible in the presence of a strong electrical or gravitational field, the first, near the atomic nuclei, and the second at the surface of very dense stars.

The phenomenon can be easily observed in a gas-filled cloud chamber. Gamma-rays are invisible, but now and then the tracks of two charged particles become visible, coming from a single point, and these tracks are twisted in opposite directions by the external magnetic field of the cloud chamber. In other respects the tracks are identical and indicate that these particles possess equal energy, velocity, and mass, and are oppositely charged.

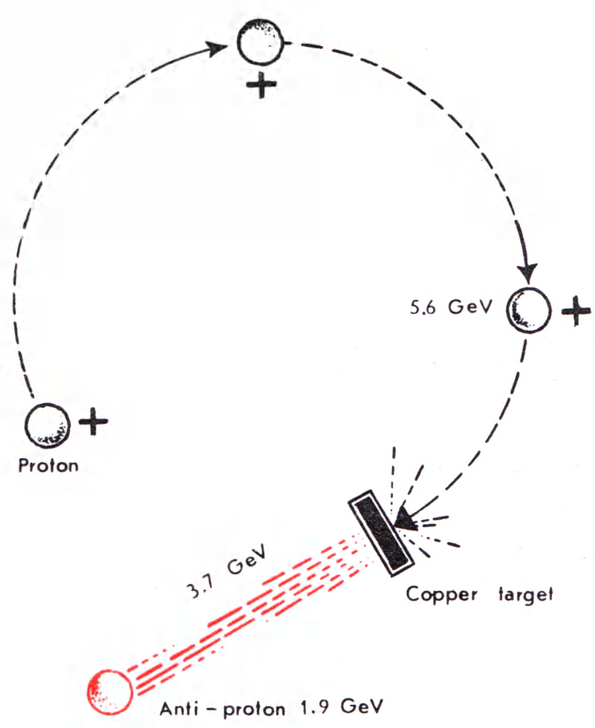
The energy involved in the formation of an electron-positron pair is double the rest energy of a solitary electron (0.51 MeV), calculated from the formula $E=m_0c^2$, and amounts to 1.02 MeV, an energy easy to produce using gamma-radiation from ordinary radioactive sources.

There Should Also Be an Anti-Proton

A rather different picture was obtained when attempts were made to advance the theory of the proton. Its magnetic properties as measured proved to be three times as large as those calculated from Dirac's equations. The actual and theoretical results would only coincide if allowance were made, by analogy with the electron and positron, for the existence of a particle of equal mass to the proton but with a negative charge.

Whereas the existence of the positron was quite easily confirmed experimentally in due course, it was impossible for a long time to identify the particle that was the opposite of the proton.

The proton is 1 836 times as heavy as an electron, and to produce a pair of protons and anti-protons there must consequently be available a source of energy of a power considerably exceed-



What was needed to produce an anti-proton

ing 1 800 million electron-volts, i.e. an energy of 936 MeV for each nucleon. Particles of such energy could only exist in cosmic radiation.

Once scientists took for negative protons the negative particles, heavier than an electron, identified in cosmic radiation, but these particles proved to be mesons, whose mass was no larger than one-sixth that of a proton.

Having failed to identify negative protons in cosmic radiation, many scientists began to question the very existence of such particles. But other asserted that it had proved impossible so far to identify negative protons only because there would not be enough of them in cosmic radiation, if they possessed all the properties attributed to them by theoretical physicists. No one succeeded in identifying the elusive particles, but a quite delicate and clever method for detecting them was developed.

A little later discovery of the anti-proton was reported from different laboratories, but these reports were not substantiated convincingly enough.

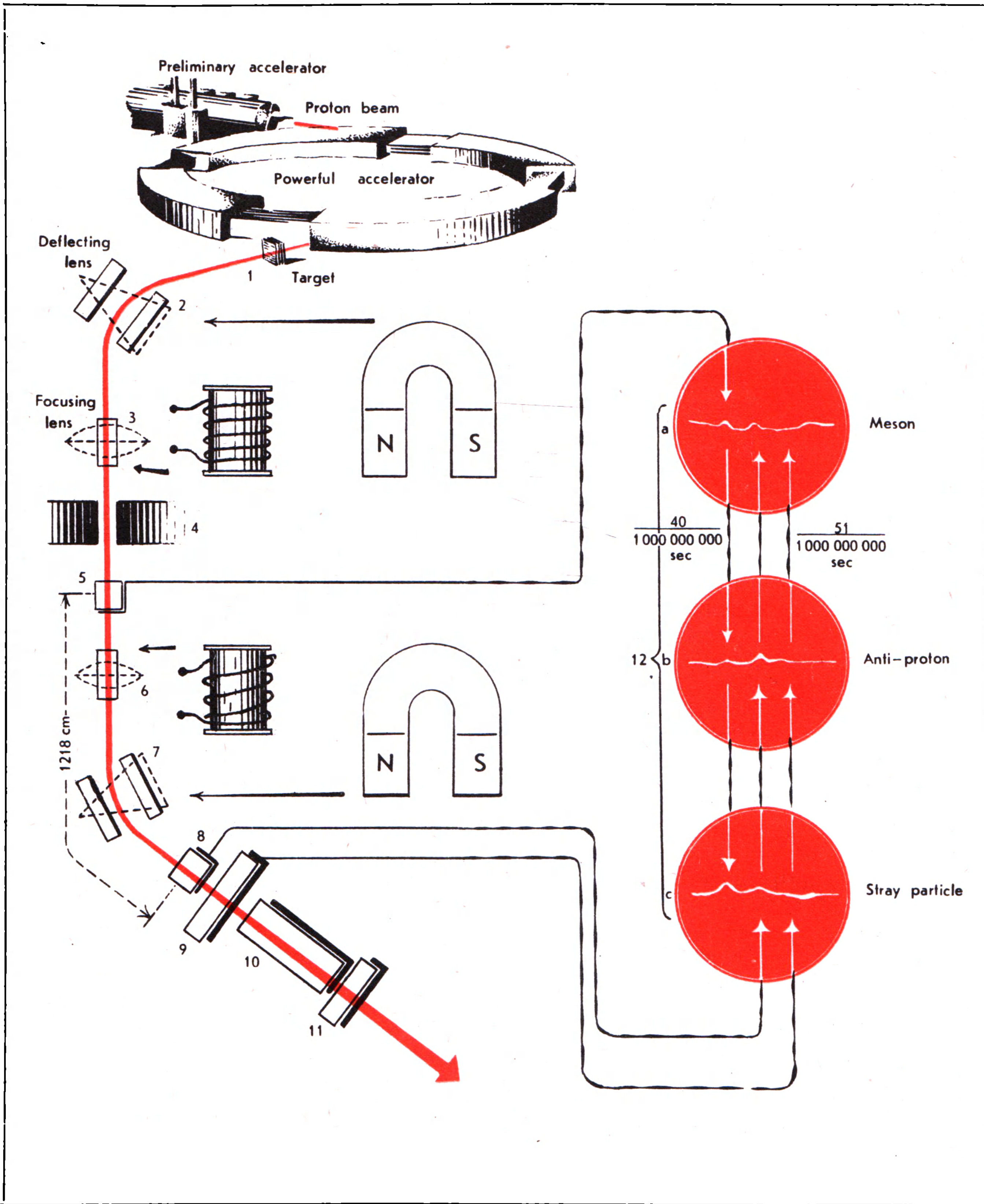
Great hopes for a solution of this exciting puzzle and for obtaining the new particle artificially were raised when an accelerator was commissioned at the University of California, capable of accelerating particles to energies of 6 200 MeV. When a proton, accelerated to 5 600 MeV, hits a proton or neutron of another atom, the particle affected flies aside, carrying away two-thirds of the energy imparted to it by the collision, while a third of the energy (1 900 MeV) remains free to give rise (or 'birth') to a new particle.

Let us consider this phenomenon in rather more detail.

Any event occurring in the microworld can be considered an isolated one, since the distances across which particles interact are usually infinitesimal (10^{-13} cm) compared with the distances between neighbouring atoms (10^{-8} cm).

Therefore, in an isolated collision of two nuclear particles, or when they react with each other, or during spontaneous disintegration of a nucleus, the total energy of the particles does not change.

'A needle in a haystack'. Diagram of the highly intricate system that scientists had to develop in order to identify, separate, and measure the anti-proton: *1*—the beam of protons, mesons, hyperons, and other particles, knocked out of the copper target of a particle accelerator, also contains a certain number of antiprotons; *2*—magnetic lens, deflecting all negatively charged particles (light mesons) lighter than the anti-proton and arresting all positively charged particles (protons, mesons, etc.); *3*—magnetic lens focusing into a narrow beam all the negatively charged particles that have passed the preceding lens (anti-protons, heavy mesons); *4*—concrete wall, isolating the particle accelerator from the premises accommodating the measuring instruments; *5*—first scintillation counter recording the time of passage of a negatively charged particle; a second record is made by similar counter, *8*, located 1 218 cm away from the first; if a particle covers this distance in 40 nanoseconds, the particle is a negatively charged meson, but if the particle flies across this distance in 51 nanoseconds, it is an anti-proton; *6*—another focusing lens, gathering particles in a narrow beam; *7*—magnetic lens deflecting anti-protons from still heavier particles, hyperons; *8*—second scintillation counter, making a second record of the flying particle; *9*—first checking Cherenkov counter; the material used in the counter glows only when the velocity of a passing particle is 75-78 per cent that of light, i.e. when that particle is an anti-proton; *10*—second checking counter, which begins to glow only when a particle passes through it at a velocity above 78 per cent that of light, i.e. when the particle is not the anti-proton looked for, but some random heavier particle or a particle that entered the carefully shielded beam from outside; *11*—final scintillation control that makes it possible to check whether the particle sought and identified has after all passed through the whole intricate system from beginning to end; *12*—the pictures appearing on the screens of measuring instruments when the particle flying through the system is (*a*) a meson; (*b*) an anti-proton or (*c*) a still heavier particle



Preliminary accelerator
Proton beam
Powerful accelerator
Deflecting lens
1
Target
2
Focusing lens
3
4
5
6
1218 cm
7
8
9
10
11
N
S
N
S
Meson
a
40 / 1 000 000 000 sec
51 / 1 000 000 000 sec
Anti-proton
12
b
Stray particle
c

Their energy always comes from one of two sources: (1) when the particle is decelerated, part of its kinetic energy is released; (2) if a particle with mass is split (smashed) a fraction of its intrinsic energy is released, accompanied with a corresponding decrease in its mass, in strict accordance with the law of the interdependence of mass and energy. By analogy, energy can be expended in one of two ways: (a) either on acceleration of the particle (with a corresponding increase in its mass), or (b) given sufficiently large energy, on producing a new particle.

The setting-up of the experiment was very thoroughly considered, its idea was as follows. A flux of protons, accelerated in a synchrophasotron, was directed at a copper target placed inside the vacuum chamber of the accelerator. As a result of collisions between the accelerated protons and nuclei of copper negative protons should be knocked out together with other particles, moving in the direction of the protons that knocked them out. But owing to the fact that anti-protons carry a negative charge, the magnetic field of the accelerator bends their path not toward the inside, along the circumference of its vacuum chamber, but to the outside, that is, forces the particles to leave the vacuum chamber through its wall.

The beam of anti-protons is then passed through multiple-slot filters placed in the field of another strong magnet, the slots being so selected and arranged in respect to one another that all particles, differing from anti-protons in velocity and mass (mesons, and especially hyperons) would be arrested in the filters, while the separated anti-protons would be passed on to a recording device.

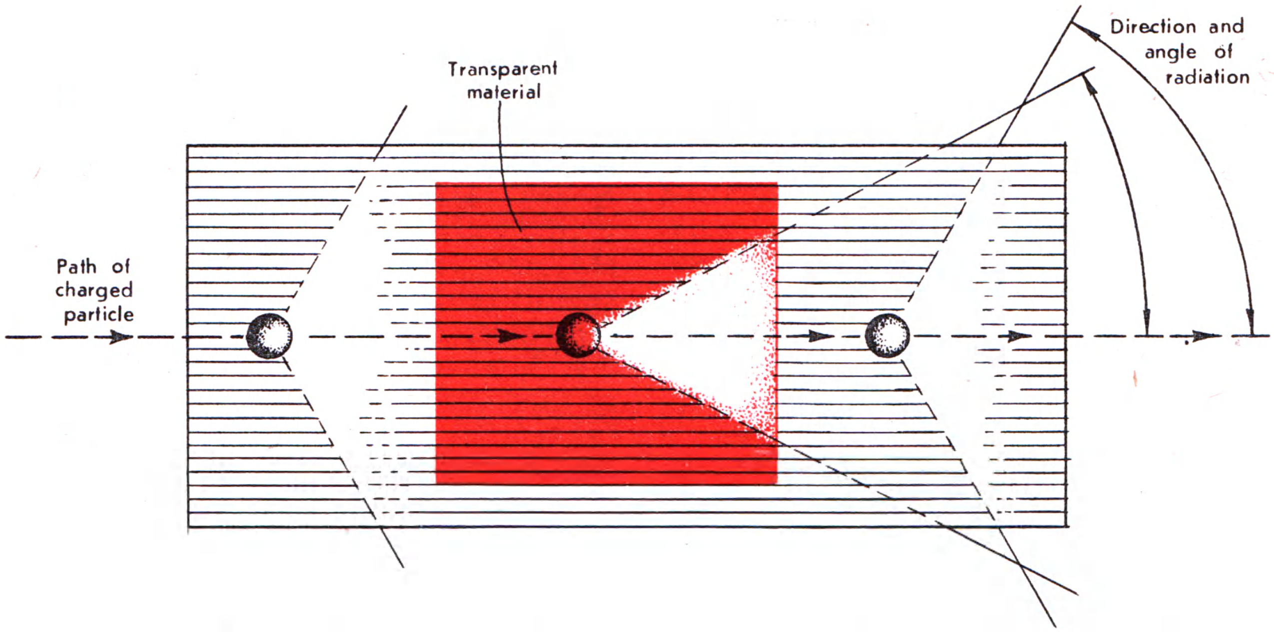
As a recording device it is possible to use either stacks of stripped emulsion (without backing) on which the anti-protons leave their tracks, or counters that react to light radiated by a transparent body when such fast charged particles pass through them, or counters based on what is called Cherenkov radiation.

Normally, whenever it is a matter of the velocity of propagation of light or other electromagnetic radiation, a figure of 300 000 km/sec is cited. Apart from the fact that the exact velocity of light is 299 998.6$\pm$0.5 km/sec, it only holds for the propagation of light in a vacuum. And no body and no natural physical process can exceed this velocity.

In other media, however, for instance, in the atmosphere, or water, or glass, or substances, the velocity of light may be less than its velocity in a vacuum.

This explains the confusion experienced, when one encounters in the description of a physical process an assertion that a particle (usually an electron) moves with a velocity greater than that of light. What it means is that in the given medium the electron moves with a velocity greater than that of light in that medium.

The essence of this famous phenomenon, named after its discoverer, the Nobel prize winner P. Cherenkov (who discovered it jointly with S. Vavilov), is that a particle moving with a velocity greater than that of light (in a given medium), itself radiates light. The new radiation possesses several remarkable properties. It does not spread in all directions, but in the form of a cone (or funnel), whose axis coincides with the direction of the particle's travel. The cone angle, or the angle between the direction of light emission and the path of the initiating particle, is strictly dependent on the velocity of the particle and, naturally, on the refraction index of the substance for the wavelength of the light emitted by the particle. The



Cherenkov radiation only appears when a particle passes through a transparent medium (liquid, plastics) at a velocity exceeding that of light in that substance

greater the velocity of the particle, the narrower the cone is.

The brightness of the radiation increases with the velocity of the initiating particle and is directly proportional to its electric charge.

The emission angle, and the duration and brightness of the flashes of light are so sensitive to particle velocity and the physical properties of the material that, apart from the great scientific importance of the discovery, they enable it to be used in instruments of exceptionally high accuracy for measuring the velocity and direction of the fastest charged particles (electrons, protons, and mesons).

As it passes through a substance, the particle excites atoms along its path, which begin to emit light just as soon as the particle reaches them and imparts a fraction of its energy to them.

And since electromagnetic waves are not emitted by all the atoms at once, but gradually, they are damped in all directions, owing to the interference of light waves, except the one that coincides with the path of the particle.

This phenomenon rather resembles the wake of a fast speed boat, the two stern waves spreading apart as its speed exceeds the rate of wave propagation on the surface of the water.

By passing a flux of investigated particles through a succession of counters, based on this phenomenon, and measuring the brightness and angle of emission of light in some material, it is easy to determine the velocity of the particle; and, by using this counter in an arrangement with other counters and instruments it is possible to measure the mass, charge and other characteristics of the particles investigated. Counters of this kind are referred to as Cherenkov counters or detectors.

In addition, the belief that the new particle appears extremely rarely has also been confirmed. It has not been possible to identify more than 20 anti-protons a day. The life of an anti-proton is one tenth of a microsecond (i.e. one ten-millionth of a second). The annihilation of an anti-proton, as it combines

with a proton releases an energy of 900 MeV.

Unlike the process of electron-positron annihilation, in which two quanta of energy (electromagnetic radiation) are emitted, the combination of a proton and anti-proton does not cause such radiation, but gives rise, instead, to a certain number of mesons.

Can Anti-Matter Exist?

The discovery that proved it possible for there to be protons and electrons with positive and with negative charges, gave grounds for asking why are all the protons of the matter around us always positive and the electrons negative?

Could there be substances whose elements consisted of atoms with nuclei built up of negative protons, with positive electrons (positrons) rotating in their electron shells? It is easier to pose such questions, like so many others, than answer them.

If such a form were possible, there would be grounds for supposing that the physical structure of the world around us that we know is a local phenomenon characteristic only of our Solar system, and possible only in our Galaxy. And it might be that other galaxies are built up from matter whose atoms consist of negative protons and positive electrons.

To prove that, however, by conventional astrophysical methods of observation is impossible. Such matter, belonging to a reverse or anti-galaxy, on encountering the matter of our ordinary Galaxy, would immediately disappear (or be annihilated) in so tremendous an explosion that the most fervid imagination cannot conceive it.

The fact that the cosmic radiation recorded on Earth contains many protons and practically no anti-protons is explained by advocates of the existence of anti-matter as being due to cosmic rays that originate within our Galaxy, and from meteorites striking Earth.

Not so long ago, however, a group of physicists at Columbia University, using a 30 GeV particle accelerator, succeeded in identifying the first atomic particle of anti-matter, the anti-deuteron, consisting of an anti-proton and an anti-neutron. The whole experience of contemporary astrophysics and astronomy, however, indicates quite definitely that our Universe consists of identical matter, and that only its modes of motion vary.

Are There More Symmetries in the World of Microparticles?

The discovery of anti-particles, of the positron and anti-proton, suggested to scientists that other material particles of the microworld should have similar anti-particles, in particular the neutron. Though it is rather difficult to imagine what the properties of an anti-neutron would be, since the neutron has no electric charge! Anti... what?

But fairly recently scientists succeeded in identifying just such a new particle, the anti-neutron.

It had long been known that a fast proton, flying through an atomic nucleus, could lose its electric charge and emerge as a neutron. It turns out that the 'edge' of one nucleon collides with the 'edge' of another, while their neutral regions or cores fly past one another without interacting. The colliding outer section (or shells) of the nucleons form a cluster of excited nuclear matter, a 'fiery sphere', 'ball of fire', as it is referred to by physicists. It is unstable and rapidly 'disintegrates' into mesons, once more confirming the view that a nucleon should not be considered as something homogeneous. It is most probably a formation resembling the terrestrial globe and its atmosphere of gra-

dually diminishing density. Exactly the same suspicions soon arose regarding the anti-proton; and, in fact, soon after it was discovered, it was found that the anti-proton, identified by its velocity and charge, turned into a neutral particle, as it passed through a scintillation counter. This conclusion was based on the fact that the flash of light appearing in the counter was much weaker than the flash provoked by a proton flying at equal velocity.

This neutral particle, however, on then passing into another counter, vanishes in an explosion, and that can only happen if the neutral particle is the anti-particle of the neutron, or an anti-neutron.

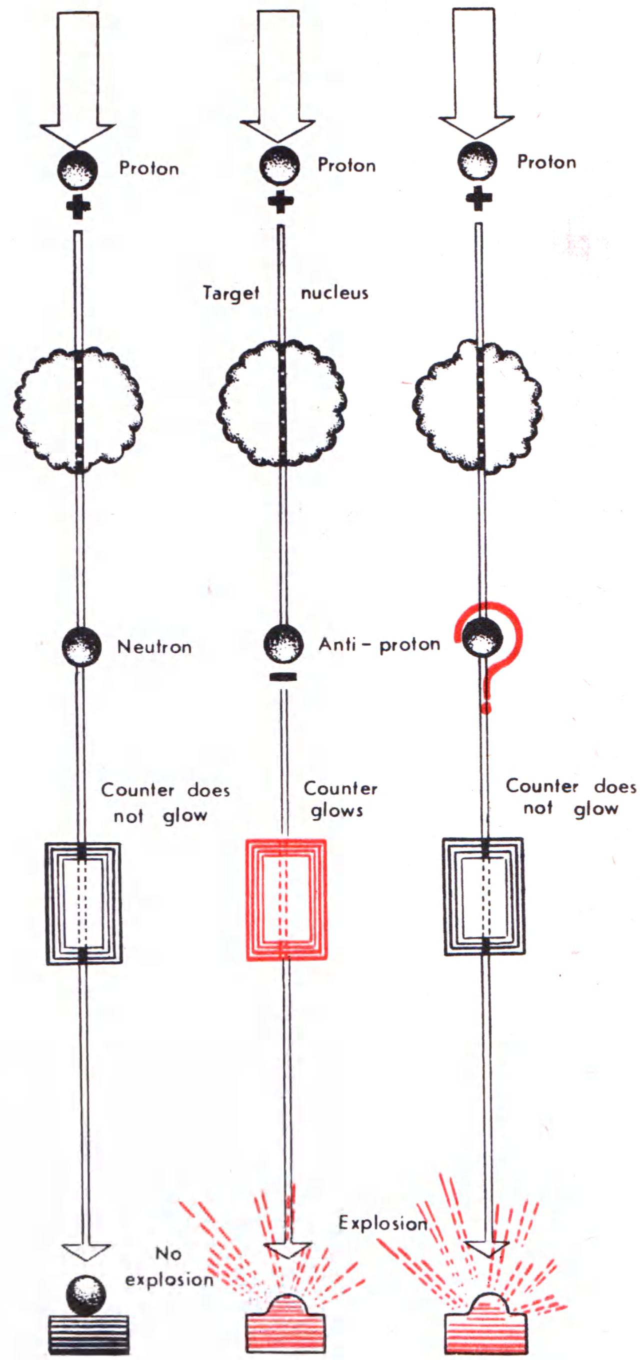
Thus, this new particle can be identified only through its self-destruction on meeting an ordinary neutron. By 'self-destruction' of the anti-neutron and neutron here is meant their transformation into other particles, e.g. into pi-mesons.

How then does an anti-neutron differ from a neutron?

Not possessing an electric charge, a neutron cannot have a mirror-image opposite particle, with a charge of some unusual sign. But it has a number of other properties in respect of which features of an opposite kind can manifest themselves; for example it behaves as a small permanent magnet. Consequently, an anti-neutron can also behave as a magnet, but of opposite polarity, and since the magnetic properties of particles depend on their direction of spin, it would seem that the anti-neutron spins in the opposite direction to a neutron.

Thus it has proved feasible quite convincingly to detect anti-particles of all the ordinary particles from which matter is built up.

But what about mesons and the other new particles?



Diagrams representing the experiment that enabled the anti-neutron to be identified. A particle that causes no glow as it passes through a scintillation counter but is annihilated with an explosion after hitting an encountered atom of matter placed in the counter can be nothing else than an anti-neutron colliding with a neutron (on the right)

How 'Elementary' are Elementary Particles?

As scientists penetrated deeper and deeper into the mysterious interior of the atomic nucleus, the means used by them became more and more exhausted, and all that was left were the fluxes of various accelerated particles produced in accelerators for smashing or 'probing' one particle or another.

From the time they became armed with powerful, and then superpowerful 'atomic artillery', sensational discoveries were made, one after the other, perhaps, more frequently than was to be expected. In the first place, new particles were discovered. The energy of 'atomic projectiles' measured in millions of electron-volts, proved sufficient to enable scientists to detect the positively charged electron or positron among the debris of 'microdisasters'. Accelerators, rated at hundreds of millions of electron-volts, made it possible to produce mesons artificially, which had first been identified in cosmic rays. And the building of accelerators capable of developing energies of thousands of millions of electron-volts led to the discovery of anti-particles (the anti-proton, anti-neutron, and others).

By now about 16 elementary particles are known and about as many anti-particles and if we include the very short-lived particles, the so-called quasi-particles (or *resonance* particles), then the list of known elementary particles is much longer.

Most of these particles are unstable. They disintegrate in an incredibly short time, and undergo a number of radioactive disintegrations (with emission of beta-particles), turning into a few, already stable particles of smaller mass (electrons, protons, gamma-quanta, and neutrinos).

As far as could be established, none of these definitely existing elementary particles could be broken down into smaller constituents, so they were all considered to be elementary particles meaning that they had no structure. In other words, these particles could not be imagined as consisting of other particles of any kind. The unstable particles fall into two groups. One of them includes particles heavier than the electron but lighter than the proton, which are called mesons. The other group includes particles heavier than the proton referred to as hyperons, which disintegrate only into nucleons. Three types of meson are known: mu-mesons, pi-mesons, and *K*-mesons. The mass of a mu-meson is approximately one-eighth, the mass of a pi-meson about one-seventh, and the mass of a *K*-meson about one-half that of a proton. Mu-meson can only be negative or positive, and no neutral mu-mesons are known. Their mass apart, mu-mesons seem to be completely identical with electrons, and may be regarded as heavy electrons. No other heavy electrons, however, are known to exist in nature.

The anti-particle of the negative mu-meson (μ^-) is the positive mu-meson (μ^+).

As soon as a mu-meson appears it splits into an electron and two neutrinos:

$$\mu^- \rightarrow e^- + v + v$$

Because of this interaction, all three particles have much in common and have therefore been called leptons, or light particles.

Pi-mesons may be negative, positive, or neutral (π^-, π^+, π^0). The anti-particle of the positive pi-meson is the negative pi-meson. Pi-mesons are easily produced by bombarding nucleons with particles or radiation quanta possessing energies of several hundred million electron-volts. The kinetic energy of the nucleons is then converted directly into the rest

mass of a pi-meson, and a whole range of reactions is possible, as follows:

proton + proton → proton + neutron + positive pi-meson;
proton + neutron → proton + proton + negative pi-meson;
gamma-quantum + proton → neutron + + positive meson;
gamma-quantum + proton → proton + + neutral pi-meson;
gamma-quantum + neutron → proton + + neutral pi-meson;

and so on.

The charged pi-mesons produced by high-energy accelerators disintegrate as follows: *positive pi-meson*: positive mu-meson+neutrino, or positron+neutrino; *negative pi-meson*: negative mu-meson+ +anti-neutrino, or electron+anti-neutrino with a half-life of 2.6×10^{-8} sec. A neutral pi-meson disintegrates much more rapidly, but only into two photons with a half-life around 4×10^{-16} sec.

Positive and neutral K-mesons (K^+ and K^0) are known, and corresponding anti-particles: negative (K^-) and neutral (K^0) mesons.

Owing to its large mass the K-meson can disintegrate in many possible ways. The half-life of a charged K-meson is 0.85×10^{-8} sec.

The elementary particles heavier than the proton exist in three kinds, the hyperons, denoted by Greek capitals: Λ (lambda), Σ (sigma), and Ξ (xi). All hyperons disintegrate into nucleons. Each hyperon has an anti-particle of opposite sign.

Thus, the world of elementary particles turns out to be exceptionally rich both in variety of particles and in types of interaction and mutual transformation.

Can a Part Be Larger Than the Whole?

A more or less satisfactory and reasonable system has been worked out to classify these particles and their interactions; but it is still far from a harmonious picture, and the kinds of particles and types of interaction observed have not yet been linked with each other.

Contemporary theory supposes that a nucleon may consist not only of pi-mesons, but also of pairs of nucleons and anti-nucleons while an electron may 'incorporate' electron-positron pairs, and even nucleon-antinucleon pairs. A meson may consist of three mesons, and so on.

A new, previously quite unknown situation arises. We are accustomed to the fact that something big can consist only of smaller parts (the atom of a nucleus and electrons; the nucleus of nucleons), that a part is always smaller than a whole, that the seeds of a watermelon cannot be larger than the melon itself.

Then how can a nucleon-antinucleon pair be the constituent of an electron? But modern physics maintains that particles can consist of one another and, furthermore, that the larger can be contained in the smaller.

Here the words 'include' and 'consist' must be understood in a dynamic (continuously changing) sense, rather than in a static (immobile) one, i.e. in the sense that when a particle (e.g. a nucleon) interacts with another particle (say a photon) the presence of other particles acting as intermediaries is inevitable (such as mesons, nucleons, anti-nucleons, etc.), appearing temporarily as a result of the interaction.

Miracles do not happen here, either. The question is not one of what appears from what, but of the energy that one particle or another possesses at a given moment, and what part of that energy, on turning into mass, contributes to the appearance of another new particle of some kind. Everything is then more or less clear. A particle of higher energy

(even if it is of smaller mass in its ordinary state) can give rise to a particle of larger mass because of its excess energy. We must just not forget Einstein's law, that mass is interrelated with energy.

The particles contained inside another particle are closely bound to each other. But this bond requires the expenditure of colossal energy so that a quite considerable part of the mass (sometimes even all) of the incorporated particles is expended on this binding energy. So, the 'strangeness' of the things considered in our story is explained by the mass of an elementary particle being equal to the total mass of its constituent particles minus the binding energy, on which a considerable fraction of the mass of the interacting particles is expended. When two elementary particles of tremendous energy collide, they must split into their constituent particles, and their masses will increase appropriately on account of the energy imparted to them.

For that reason we cannot consider a particle as something invariable, like a solid charged ball of constant mass and a very definite amount of energy.

We repeat, theory suggests. But attempts to build complicated models of particles, in which some of them appear to be intricate systems consisting of other, more elementary particles, and so with a large mass defect, have so far proved unfounded.

Above we have been concerned with the destruction, and fragmentation of elementary particles, and the unexpected consequences of such micro-disasters that spoiled the game of scientists, but as a matter of fact, opened up new, unfamiliar pathways to the secrets of the structure of matter. The results obtained, however, did not remove the problems of the structure of elementary particles, at least of those that can still be rightfully considered elementary, i.e. the proton, neutron, and electron.

Summarizing what we have said, we can state that whenever there is a collision between elementary particles accelerated to high energies, it results not in *mechanical splitting* of the particles involved into still smaller ones, but in the *transformation* of some particles into other lighter ones. Mutual transformation is the general and the most characteristic property of elementary particles. There are only two abnormal particles that do not obey this rule, the proton and the electron. For them, the process of disintegration, or rather transformation, into other, lighter particles is forbidden. This exception makes possible the existence of a more or less stable material world around us.

Thus, in the nuclear reaction known as positron decay,

$$p \rightarrow n + e^{+} + v,$$

where p is a proton, n is a neutron, e^{+} a positron, and v a neutrino.

One of the reaction products, the neutron, has a larger rest mass than the original particle, the proton, although it is formed together with two other particles from the proton, and, being a 'part' of it, should possess a smaller mass than the whole particle.

All this means that the concepts of classical physics about parts and wholes do not apply here.

The formula shows how complex a proton is, for it gives birth to three particles, a neutron, a positron, and a neutrino. That does not, however, mean that the proton consists of these three particles, if for no other reason than that the proton does not contain them. In addition, the proton takes part in many other reactions, resulting in the appearance of the most diverse particles, and we should have then to suppose that they are all its constituents.

When the energy involved in the collision of a proton with other particles is comparatively small, the proton sometimes behaves like an elementary particle.

We have already said that the proton is not a homogeneous sphere and that at its centre or core there is no electric charge. The charge is arranged on the ring-like outer pulsating shell, which consists of a cloud of pi-mesons. When attempts were made to bombard the proton, or rather its pi-meson cloud with pi-mesons, new particles appeared, *K*-mesons and hyperons, and also anti-particles (anti-protons and anti-neutrons). They all appeared during the collisions of pi-mesons with protons, but only when a pi-meson hit the core of the proton, and not when it merely pierced the mesonic cloud. Hyperons, anti-protons and anti-neutrons appeared when pi-mesons came quite close to the core.

That encouraged the conclusion that the core of a proton was not continuous but consisted of several shells, a *K*-meson shell on the outside, then a hyperon shell, an anti-proton shell, and an anti-neutron shell. And the real, 'bare' proton was hidden somewhere in the very depth of this core. All these particles, it seemed, were 'spread' on their shells like the pi-mesons in the outer, pulsating cloud. 'Probing' of the structure of one of the elementary particles, the proton, by means of a beam of electrons accelerated to several thousand million electron-volts (GeV), and then also by pi-mesons, has again brought us up against the energy state of particles, and explained the seemingly inexplicable, namely, why particles of a larger mass (hyperons and anti-hyperons) manage to find room, not just for one but for several at once, within the much smaller volume (or rather mass) of the proton. For a certain time this larger mass, like a tightly wound spring, is invisibly present in the energy of the smaller particle, until it turns into the mass of the particles involved when it leaves the narrow 'dungeon' of the proton.

The despair of scientists became greater still when it became clear that, as the energy of particles was increased in accelerators, so the number of new kinds of particles increased, with all of them inevitably undergoing a series of disintegrations and transformations from one into the other. And the higher the energy of each of the newly discovered particles, and the bigger the particle into which it was transformed at the very beginning of the decay process, the shorter its life was.

Nature does not like complicated things. Everything complicated is, as a rule, unstable. In the final analysis very simple things underlie all the laws of nature and natural phenomena, and it is only the way to understanding them that proves to be complicated. In short, these complications are to be found not in Nature, but in the heads of scientists. And indeed, in spite of their great variety, the transformations of particles obey certain laws; heavy particles, for instance, cannot of themselves turn into light ones, electrons cannot turn into photons, and so forth.

So, perhaps the clue to the great complexity and abundance of elementary particles is concealed in a very simple idea, namely, they are all nothing but various energy states of a small number of truly elementary particles, and that all their other properties, attributed to other particles, are abnormal states attributable to extreme overloading with energy.

The known American physicist, Victor Weisskopf, for instance, believes that there actually exist only two elementary particles, baryon and lepton. Baryons are protons and neutrons, and leptons

electrons. mu-mesons, and two kinds of neutrinos. But as a matter of fact, the basic elements of matter are only the proton and the electron.

Pi-mesons and K-mesons are packets of energy emitted by baryons, and the strange particles (lambda, sigma, and xi) are excited baryons.

Only the future, and that seemingly not so distant, will show whether these ideas are correct. At present one thing, and one only, is clear: the greater the number of particles available to scientists, the greater will be the probability of discovering laws enabling their great variety to be reduced to a minimum number of truly elementary particles.

When Two Times Two Is Too Much

Men would never have released the fabulously vast energy hidden in the atom, if they had contented themselves solely with discovery of the atomic nucleus and its electron shell for it was the endeavour to understand how the nucleus was built that made it possible to discover the wide family of elementary particles and the amazing truth that when Nature built the atomic nuclei of existing elements out of them, she proceeded amazingly stingily and purposefully, but by no means 'wisely'. Men have learned how to 'repack' atomic nuclei much more densely than had ever been done by the blind forces of Nature, and turned the energy released to their own advantage.

So it is not surprising that, having created such fine research instruments as particle accelerators, scientists wanted to investigate to the end or, at least, to penetrate as deep as possible, into the microworld.

Scientists were overjoyed as they created particle accelerators of higher and higher power, for each new energy range attained with the 'projectiles' of their 'atomic artillery' disclosed the existence of newer and newer particles, first single ones, then pairs, and later dozens. Theoretical physicists predict that the time is not so distant when particles will be identified in hundreds.

All that cost an enormous amount of money apart from the labour and efforts of a whole army of experimenters. Each next generation of more powerful accelerators required the manufacture of magnets weighing thousands and thousands of tons, accelerating chambers whose dimensions are measured in kilometres, and the whole installation and buildings began to approach geographical objects in size, and microscopes as regards the accuracy with which they were made.

And of course, the cost of such structures rises accordingly.

And although the energies imparted to particles by the accelerators so far built boggle the imagination—33 000 million electron-volts (33 GeV), and at the big Soviet accelerator at Serpukhov 70 GeV—men have only begun to probe the spectrum of energies existing in nature; particles are encountered in cosmic rays with energies of 10^{20} electron-volts, ten million million giga-electron volts!

Compared with these natural accelerators of truly cosmic scale even the grandiose projects for improved super-powerful accelerators of 300 and even 1 000 giga-electron-volts pale hopelessly. And one may well ask whether there is any point in building such giants, the weight, dimensions, cost, and necessary tolerances of accuracy of which increase in cubic progression for a doubling of power. Why not try, instead, to microminiaturize accelerators?

The question has proved to be more than timely.

A very simple idea, clear even from everyday life, has been in the air for

a long time. The destructive force of a head-on collision of two motor-cars, each travelling at a speed of 60 kilometres an hour, proves to be not twice as much as when either of them crashes into a rigid obstacle but four times as much. On the same analogy if one uses a flux of accelerated particles to bombard not a fixed target but a target (or flux of similar particles) moving at the same speed toward the bombarding particles, it should be possible to obtain a four-fold gain in collision energy (in the centre-of-mass system). But things are much more complicated when particles, moving with velocities comparable or close to that of light, collide (fortunately for researchers), since it is not a matter here of purely mechanical forces, but of the magnitude of the energy involved in the various nuclear reactions. And that, it turned out, was not quite the same thing.

When an ion accelerated to high energy collides with a stationary particle in a target, its energy is expended not so much on initiating possible nuclear reactions, as on accelerating the centre of gravity of the whole system of colliding particles, as follows from the laws of conservation of energy and momentum. Consequently, the bombarding particle is never in a position, in principle, to expend all its kinetic energy, and the stationary particle-target, on being hit, must begin to move with a greater velocity, which also involves a considerable expenditure of energy. It is rather like when one tries to split a stone with a hammer. The fraction of the impact energy expended on shifting the stone, i.e. on accelerating it, is lost as regards splitting it. But if one strikes a heavy stone with a very light hammer, the stone will not be shifted much, and almost all the energy of the hammer will go on crushing the stone. But if a very light stone or pebble is hit with a heavy hammer, then almost the entire impact energy will be transferred into energy displacing the pebble, and nothing will be left to split it. Finally, if the hammer and stone are of equal weight, impact will be such that they will move together with a velocity equal to half the initial velocity of the hammer; the hammer will lose velocity and the stone gain it.

To determine the fraction of energy that can be spent on initiating the reactions that interest us (e.g. reactions resulting in the production of particles), it is necessary to penetrate the centre-of-mass system, in which the two particles, both the bombarding one and the target, move to meet each other. Then, there is nothing to prevent the two particles from expending all their energy at the moment of collision. In addition, other, so-called, relativistic effects (close to the velocity of light) appear on the scene, eating up a greater part of the advantage gained by increasing the energy of the accelerated particles.

We have already mentioned that the mass of a particle increases considerably as it approaches the velocity of light, i.e. the mass of our 'hammer' increases, and, consequently, we lose more and more energy in accelerating it. When a proton, accelerated to an energy of 1 000 million electron-volts (1.0 GeV) comes into collision with a stationary proton, 57 per cent of the energy (570 MeV) is spent to no purpose (or the subsequent motion of the particles), and only 43 per cent (430 MeV) is available for a nuclear reaction. When an electron is accelerated to 3 000 million electron-volts (3.0 GeV), the effective energy turns out to be 1. 150 million electron-volts (1.15 GeV); at an energy of 6.0 GeV only 2.0 GeV can be used effectively, and finally at 100 GeV the effective energy amounts to 10.5 GeV electron-volts.

A hundred-fold increase in energy, from 1.0 GeV to 100 GeV gives only a twenty-fold increase in the effective amount. Of course, we have to be satisfied with that, for there is no other way of obtaining the energy required; but such a drop in the efficiency of projectile and target collisions does not suit anybody.

Now, let us assume that, instead of bombarding a fixed target (consisting, say, of protons) with high-energy particles, we succeed in causing a head-on collision between them. At the moment of impact both particles stop instantaneously, and as a result the relativistic increase in mass, previously imparted to them, will be expended on inducing the nuclear reaction desired. Concretely, when a proton accelerated to 30 GeV collides with a stationary proton, only 8.0 GeV are effectively available, but when two protons, each accelerated to the same energy, collide, all 60 GeV are available to obtain an effective 60 GeV from the head-on collision of a moving proton and a stationary one, as occurs in ordinary accelerators, the proton would need to be accelerated 2 000 GeV.

So further progress in physical research depends not on the total energy of the colliding particles, but on the fraction that is effective.

An even greater effect can be obtained by accelerating electrons instead of heavy particles, since they have a greater velocity for the same energy. The effective energy of two electrons colliding 'in flight' though accelerated to a 'mere' 1.0 GeV (at which the mass of an electron increases by a factor of 30 000!) proves to be equivalent to the energy resulting from a collision, in which electron is at rest and the other hits it with an energy of 2 000 GeV. What is the trouble then? Why isn't this method employed?

The fact is that the matter of a target usually has a density of the order of 10^{22} nuclei per cubic centimetre, but the number of particles in the beams hitting it is thousands of millions of times fewer than in the same volume of target. That being the case, the comparatively sparse cloud of particles could shoot right through the 'line' of another, similar cloud, without causing a single collision.

Hence there is a second and perhaps more difficult task, to obtain clusters of accelerated particles of the maximum possible density that would ensure a certain real number of head-on collisions.

This problem can be solved in a rather different way. Why, for example, should scientists not force their still comparatively 'sparse' cloud of particles to encounter a similar cloud a vast number of times, thereby increasing the probability of collisions and compensating for the lack of density in the flux of particles. To do that a batch of electrons, or other particles, must be forced to circulate for a quite long time (a score of hours or longer) in a circular vacuum chamber, built in roughly the same way as the circular chambers of large synchrophasotrons (proton synchrotrons), in what are called *storage systems*.

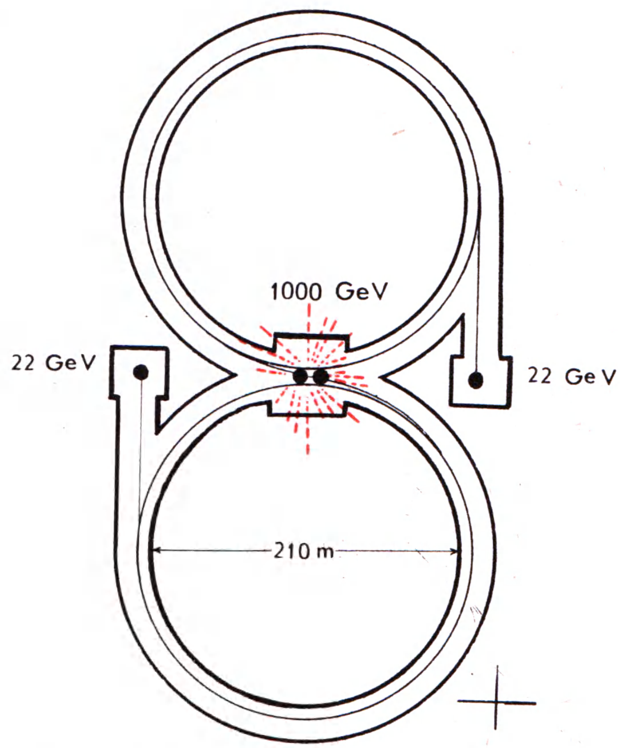
Revolving in the same orbit for many hours, particles will return to one and the same point in space after each revolution. It is not difficult to arrange for two particles (electrons, protons, etc.) revolving in two different but opposite circular orbits, to meet at that point. To do so it is only necessary to join the two orbits at a point, so that they form a large figure of eight.

Experiments on building an accelerator with colliding (or intersecting) beams of electrons began in the USSR in the 50's. The first one modestly called VEPP-1 was a magnetic track consisting of two

interconnected hollow steel rings of a diameter slightly over two metres resembling a large figure eight. Every 15 seconds a special synchrotron injected batches of electrons, preliminarily accelerated to an energy around 40 MeV into each half of the magnetic track in opposite directions. On entering the strong magnetic field surrounding the track, the electrons began to whirl around the track and were accelerated to 130 MeV, performing a complete revolution in only one hundred millionth of a second (ten nanoseconds). Since the electron clusters meet each other about 100 million times a second, head-on collisions took place from time to time, and they resulted in the release of the same effective energy as would be produced by bombarding a fixed target with a flux of electrons accelerated to 70 GeV. To obtain that energy in any other way, it would be necessary to build a cyclic accelerator seven kilometres in diameter, and a linear accelerator of the same power five kilometres long.

Taking these indisputable advantages into account the gigantic new linear or travelling-wave accelerator built at Stanford University (California) with a wave guide around 3.2 kilometres long, is fitted with storage rings, in which the energy resulting from the head-on collision of two electron beams will correspond to the energy that could be produced by bombarding a fixed target with a flux of electrons accelerated to 6 000 GeV.

Major difficulties developed at once. The beam of electrons proved not to be dense enough, with the consequence that there were very few of the head-on collisions needed. In addition, the electrons only 'scatter' on colliding, i.e. recoil from one another. And although that makes it possible to resolve many other important physical problems, other par-



Accelerator for colliding beams of electrons and positrons

ticles in practice do not arise during the collisions.

That is why, almost at the same time, the idea arose of accumulating and then colliding not two electrons but an electron and a positron.

Since electrons and positrons carry opposite charges, they will move in opposite directions in one and the same magnetic field. And only one circular magnetic path or accumulator is needed for additional acceleration and accumulation of the particles.

Although the electron-positron unit is of much simpler construction, it is very difficult to produce positrons artificially in large numbers. These difficulties, however, are more than compensated by the fact that colliding electrons and positrons are annihilated, giving birth to new particles and anti-particles.

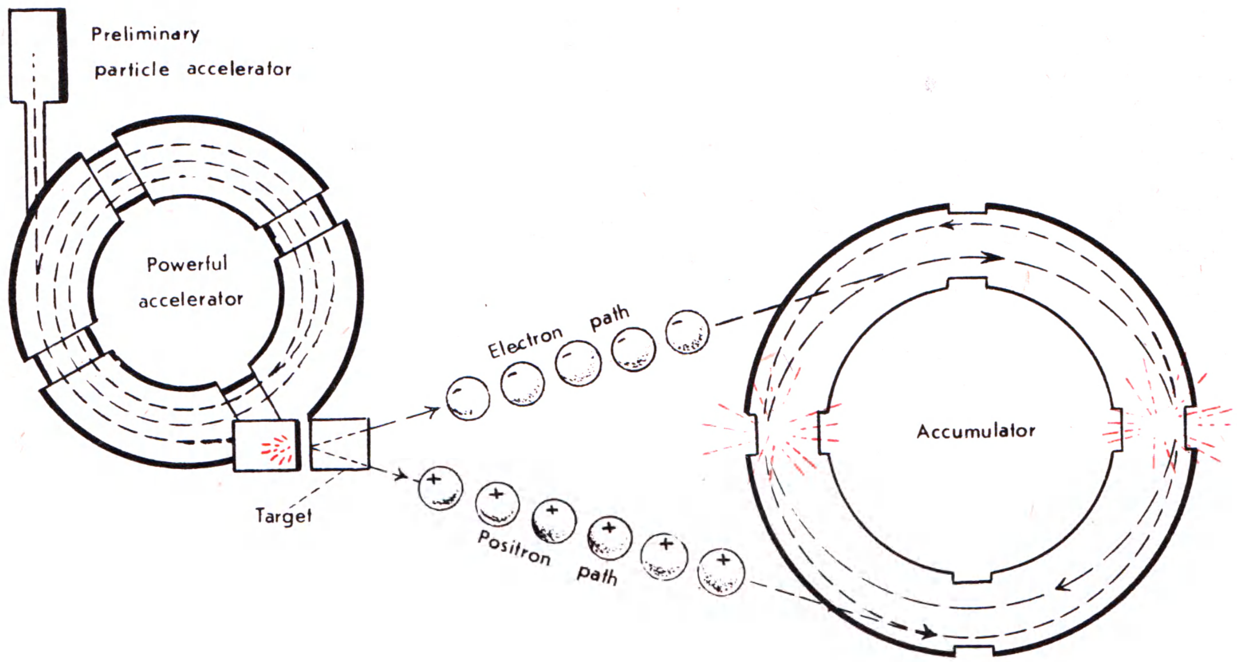


Diagram of a two-beam particle accelerator

This idea was used to build the VEPP-2 accelerator, consisting of a massive steel ring about five metres in diameter, inside which clusters of electrons and positrons, previously accelerated to around 700 MeV, are accumulated and accelerated to meet one another by the action of its magnetic field. The centre-of-mass energy resulting from their collision corresponds to the energy that would be obtained on an ordinary fixed-target accelerator if particles could be accelerated to 2 000 GeV. A linear accelerator capable of producing particles of that energy would need to be hundreds of kilometres long. The energies obtained in the VEPP-2 accelerator make it possible to produce pairs of particles even as heavy as mu-, pi-, and K-mesons.

The projects for accelerators in which protons will collide with protons present great interest.

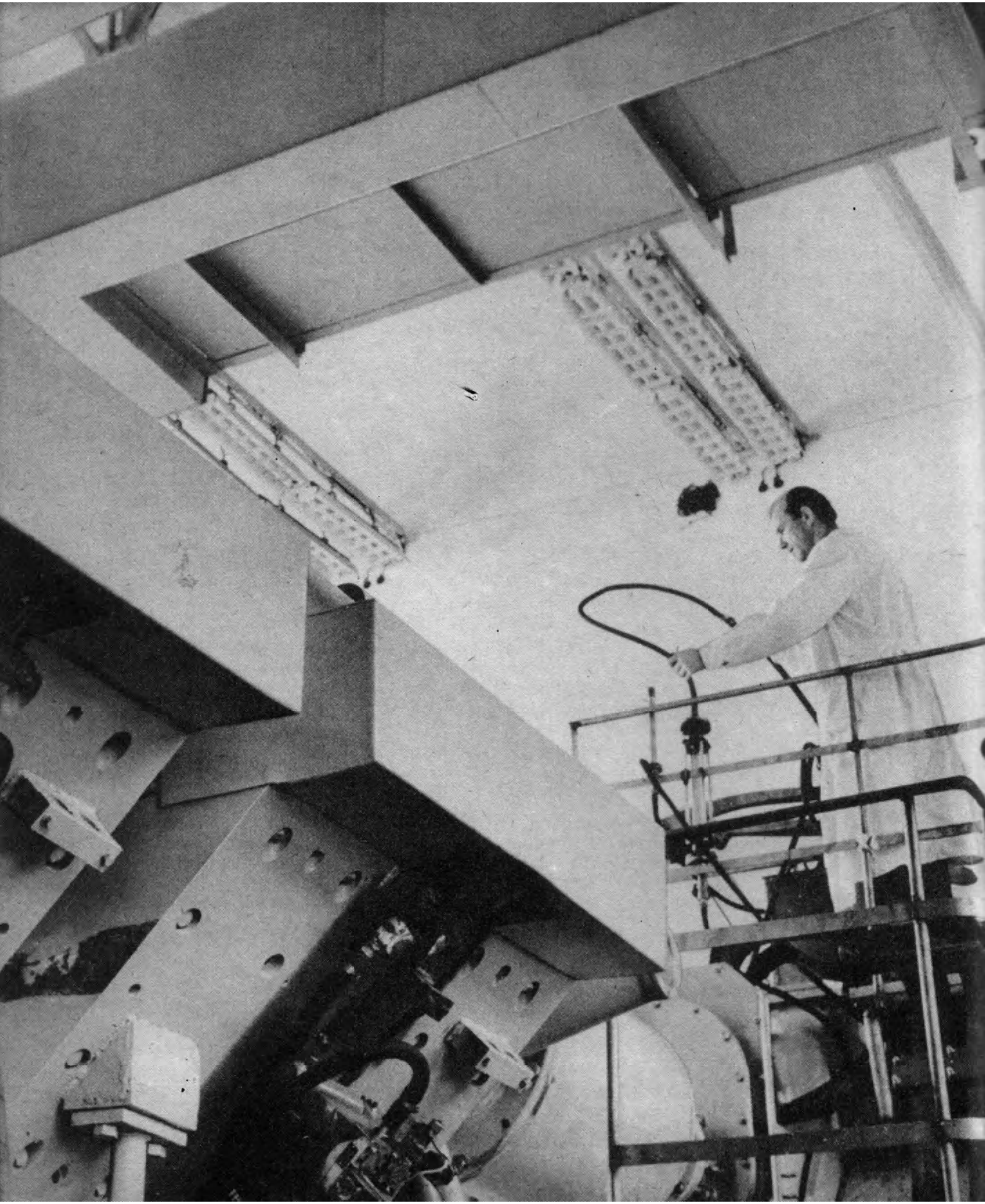
In Novosibirsk, a proton-antiproton two-beam colliding accelerator has been built, each beam of which has an energy of 25 GeV. This installation is equivalent to an ordinary accelerator with particle energies of 1 200 GeV.

Present-day engineering facilities and economic possibilities already allow one to talk of building accelerators with energies of 1 000 GeV in each intersecting beam, which would be equivalent to an ordinary particle accelerator of two million GeV.

Two-beam (intersecting) accelerators, as often happens, proved not to be a key for all locks of nuclear physics. They cannot be used, for example, to produce high-energy secondary particles like hyperons, mesons, and neutrinos. But, because they have tremendous advantages and make it possible to arrange collisions of such stable particles as electrons, protons, and their anti-particles, they have made it possible to rub out several question marks from the puzzling problems that remain. For instance, has an

electron finite size, and if so, what are its dimensions? Is space continuous or discontinuous and does it obey the law of quantization?

These accelerators make it possible to check the laws governing the interaction of charged particles across very short distances, and to obtain as much as possible information about the mysterious and still problematical anti-matter. For any anti-matter would be the ideal fuel, even more than atomic fuel. Its heat-producing value would be thousands of times greater than that of nuclear fuel, and a hundred times greater than that of thermonuclear fuel, and thousands of million times greater than that of oil or coal.



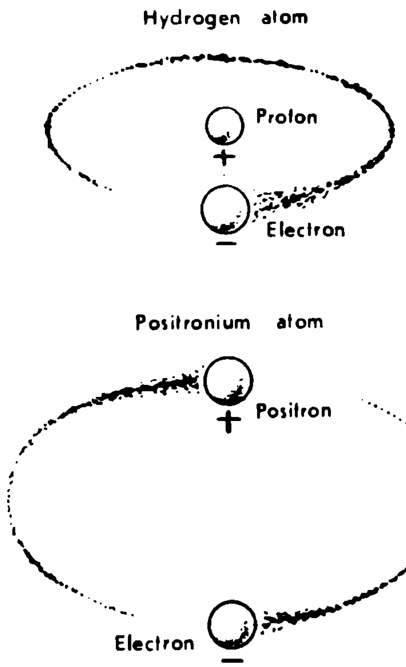
Chapter Sixteen

ARTIFICIAL ATOMS

Beginning with Rutherford's first, now classical, experiment, physicists have been smashing atoms by various methods for over 50 years, to learn what they are made of and how are they built, and the laws and forces that govern them. Even a whole jargon, characteristic of this method of research, has come into being: 'bombardment' of the atom and its nucleus, 'atomic artillery', and so on. The period of destruction in atomic physics led to discoveries of immense importance for mankind: namely, the release of intranuclear energy; the creation of new (transuranic) elements; the production of artificial radioactive substances; the discovery of new particles; and much else.

But this inevitable and necessary step in the development of atomic physics is apparently drawing to its close. The structure of the atom and of its nucleus, and the laws that govern them, although still far from being finally discovered and understood, have nevertheless armed scientists with sufficient knowledge and means to enable them to embark on a new stage that in the foreseeable future will become the most important trend in the development of modern physics, namely, the creation of artificial atomic nuclei with given properties.

When smashing or transforming atoms by bombarding them with atomic 'projectiles', scientists had an opportunity to create more or less harmonious and dependable theories that could only be finally substantiated, however, by experiments that would permit them to be used as a basis for putting smashed atoms or nuclei together or creating new, however primitive, artificial atomic structures. In the event of even partial success, perspectives would open out before them of creating not just individual atoms, but substances with the most unusual properties, superdense,



The atoms of hydrogen and positronium

superlight, or superheavy. The first such successful attempt was made in 1955, and concerned an artificial atom, the positronium.

The Positronium, an Artificial Atom

Today, many years later, everything connected with that remarkable discovery seems quite simple.

The disintegration of certain artificial radioactive elements, as we know, is accompanied with the emission of a positron. The fast-moving positron is followed at once by a free electron, which always exits in the surrounding matter.

This peculiar chase terminates in an infinitely short period of time, sometimes in only a millionth of a second and at other times even in a tenth of a nanosecond, in the appearance of a temporary, unstable atomic combination, a positronium, that has no nucleus, but in which an electron rotates with a positron about a certain common centre of gravity.

Electrically, such an atom resembles the atom of the lightest stable element, hydrogen, in which one electron rotates around a single proton; but since the positron is no heavier than the electron, the new, artificial atom, the positronium, is about 1 000 times lighter and its diameter is twice that of a hydrogen atom.

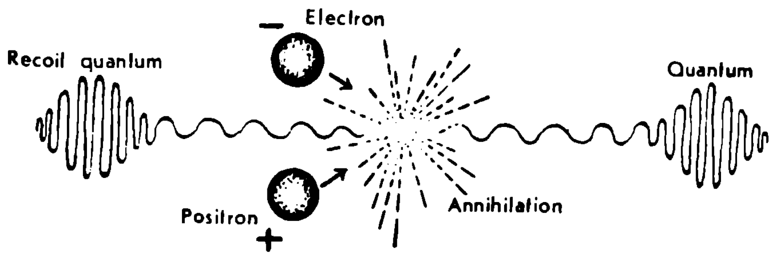
During their incredibly short life the positron and electron, nevertheless, have time to make some million revolutions around each other, then they collide and annihilate each other, and the positronium vanishes, emitting two photons.

Two Photons or Three?

The law of conservation of momentum states that the sum of the momentums of two or more interacting bodies never changes. The disappearance of a positron and electron and their transformation into radiation quanta is identical to the recoil of a gun after a bullet is fired. For every photon of radiation shot out there should inevitably be a corresponding ejection of another, exactly similar photon of like energy, in a strictly opposite direction.

The energy of a photon shot is about 1.0 MeV, 500 000 electron-volts per each photon. The positronium occasionally ejects not two, but three, photons. Theoretically, it can emit a greater number, provided the energy appearing during the transformation of the material particles (positron and electron) into photons is distributed equally between the photons.

It should be noted that no one has succeeded in directly observing the formation of a positronium. It only manifests itself at its moment of disappearance through the simultaneous identifi-



Why recoil quanta appear

cation of two or three similar quanta or radiation.

Quantum theory predicts and postulates the existence of two types of positronium: one, with a life of 1.25×10^{-10} sec, which ejects two photons when it vanishes; and another with a life of 1.4×10^{-7} sec, which emits three photons as it decays.

Ordinarily we would think that nothing important could happen in so infinitesimal a time, but in the world of atomic particles it is a very long period, quite sufficient to identify, follow up, and measure all the phases of so short-lived a process as the formation and decay of a positronium.

The two-photon positronium has been given the name 'parapositronium', while the three-photon one is called orthopositronium.

Why Spin is Also Important

In addition to mass and electric charge, an electron possesses a number of other properties, one of the most important is that it rotates not only around a nucleus, but also, simultaneously, around its axis with a constant angular velocity, characterized by a special value, known as spin.

In rotating around an atomic nucleus at a velocity several per cent of that of light, an electron imparts a peculiar 'rigidity' to the sphere describing the space where it moves.

The rotation of an electron around a nucleus can neither be accelerated nor slowed down. Nor can it be changed without destroying the electron itself.

The magnitude of spin can be expressed in revolutions per minute, and so it is measured in units of the *moment of momentum*. It is a rather complicated concept. In mechanics the moment of momentum is equal to the product of a rotating mass by its speed and distance from the centre of rotation. The higher the rate of rotation and the bigger the mass and size of the body, or the larger any combination of these values, the greater is the moment of momentum. In other words, this concept characterizes the intensity of rotation, i.e. the margin of motion. Its magnitude is related to the effort required to induce or stop rotation. A rotating electron has an infinitesimal mass and size so that its moment of momentum is therefore also infinitesimal; but on the scale of the microworld its moment of momentum is enormous.

In the microworld the spin of particles is usually measured in units of the spin of a photon, which is taken as unity. Electron spin is one-half, that is to say, half the moment of momentum of a photon. Certain particles, like pi-mesons, have no spin at all, but all others do, equal either to one-half or to unity.

When an electron and positron rotate around each other and temporarily form a positronium atom, their spins may be either parallel or anti-parallel. In the

first case, when they spin in the same direction, the resultant spin is equal to unity. In the case of anti-parallel spin, when the particles spin in opposite directions, the resultant spin is zero. This explains why two forms of the positronium are possible. In the atom of an orthopositronium the spins of the electron and positron are parallel, while in the atom of a parapositronium these spins are opposite. As a positronium disintegrates, very intricate and subtle interactions develop, in which the spins of all the particles involved in the event are of decisive importance, as well as the spins of the newly formed photons.

Photons, being one of the forms of the existence of moving matter, simultaneously manifest the properties both of particles and of electromagnetic waves. When considered as particles, they also possess spin, the value of which is unity. Photons may spin in various directions and, consequently, their spins may be added or subtracted. With parallel spin of two photons the resultant spin is equal to two; with anti-parallel spin their resultant is equal to zero.

Rotation or spin, like any other motion, obeys the law of conservation of momentum, and that explains why an orthopositronium, with a resultant spin of its two particles (positron and electron) of unity, cannot disintegrate into two photons, since the resultant spin of two photons (of unity spin each) will be zero (when they move in opposite direction) or two (when their spins are parallel). So an orthopositronium undergoes the only possible transformation: it disintegrates into three photons. The resultant spin of two anti-parallel photons is zero, while the spin of the third is unity; therefore, the resultant spin of all three is unity, i.e. is equal to the resultant spin of the positron and electron, so that disintegration is possible.

A parapositronium, on the contrary, with a zero resultant spin of its two constituent particles is easily transformed into two photons, whose resultant spin may be either unity (with antiparallel spin) or two (with parallel spin).

Owing to their spin, electrons and positrons also have magnetic properties, i.e., in rotating they behave like small magnets with poles more or less exactly directed along their axes of rotation. In an orthopositronium the north- and south-seeking poles of the two particle-magnets (positron and electron) are oppositely directed, while the electric properties of the particles manifest themselves as they spin in one and the same direction. The weak repulsion between two like poles makes the whole combination of an orthopositronium less stable than that of a parapositronium, in which the magnetic attraction tends to strengthen the electrical attraction. In consequence, the average energy of an orthopositronium slightly exceeds that of a parapositronium.

It may be that all that is much too subtle, but it plays an enormous role in determining the energy level of particles, especially when establishing why this artificial atom tends to disintegrate. Scientists have succeeded, for example, in noting that a positronium from time to time makes a sort of premature attempt to break up. The resultant spin of its particles, however, being unity, allows it only to turn into a single photon (with a spin of unity), but that, as we have already seen above, is impossible since nothing exists in nature, including the orthopositronium, that can disintegrate with the ejection of a single photon. The parapositronium, on the contrary, even does not strive to turn into a single photon, since its zero resultant spin makes that quite impossible. To make up for that, when its time comes to disintegrate, the parapositronium turns without difficulty into two phot-

ons; the spin of its particles does not interfere, as the resultant spin of the two photons is also zero. A parapositronium is therefore more stable than an orthopositronium.

Theoretical studies indicate that the difference between the energies of these two atoms is only around one thousandth of an electron-volt (0.001 eV).

The Mesonic Atom

Earlier we remarked that the carriers of the attraction forces acting between two oppositely charged particles are photons, i.e. quanta of electromagnetic radiation, continuously exchanged between the particles, while the short-range intranuclear forces owe their existence to pi-mesons (particle with a mass exceeding 273 electron masses).

In accordance with these conclusions of quantum theory, another atom not encountered in nature can exist besides the positronium—an atom with a meson instead of an electron rotating about a nucleus consisting of ordinary protons and neutrons. It is called the mesonic atom or mesonium.

Because the meson is the carrier of those still mysterious intranuclear forces, the investigation of the mesonium is of exceptional interest to nuclear physicists.

It is worth recalling certain of the structural features of an ordinary atom here, hydrogen for instance. In the hydrogen atom a single electron rotates around a proton in a circular orbit about 10^{-8} cm in diameter, while the diameter of the proton, as we know, is about 10^{-13} cm. Now, when this atom absorbs a quantum of energy, its electron leaves its normal orbit, jumping to another one more remote from the nucleus. Under the attraction of the positively charged nucleus, the electron returns, in one or more successive jumps, to its original ground-state orbit, emitting quanta of light during each jump which represent the excess energy previously absorbed.

The atoms of each element have a definite set of such orbits and therefore emit light only of a definite natural wavelength, and consequently, colour.

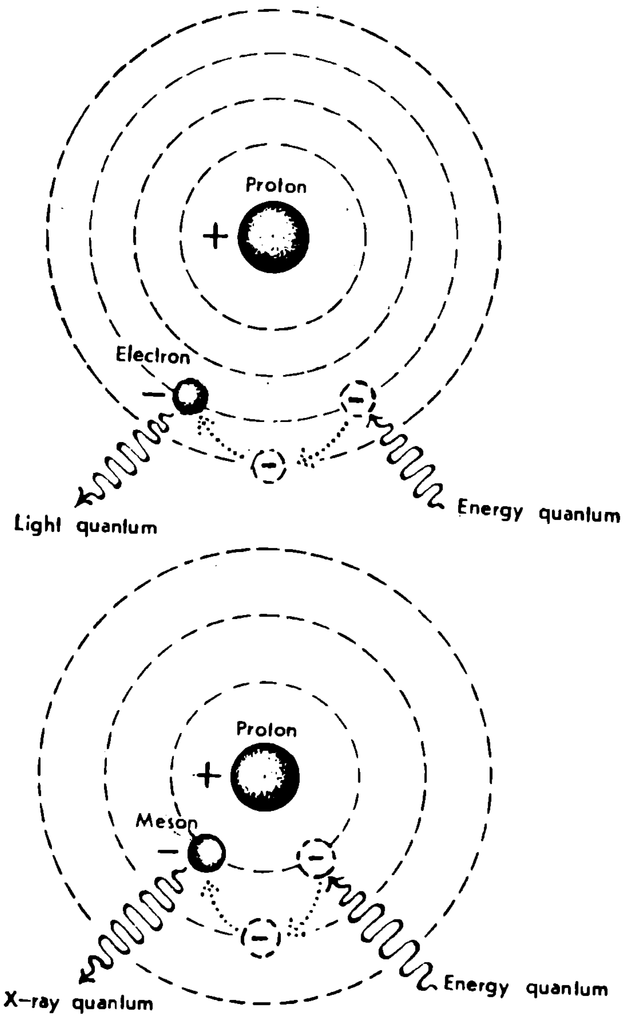
Now let us see what would happen if the electron of a hydrogen atom were replaced by a negatively charged meson. In accordance with quantum theory the meson, like the electron, will have a strictly determined number of orbits, and jumping from one orbit to another should be accompanied with a characteristic emission. With a mu-meson, weighing 210 times as much as an electron, the distance to each orbit will be 210 times less and its radiation wavelength will also, consequently, be 210 times shorter. If a pi-meson takes the place of the electron, all orbits and radiation wavelengths will be correspondingly 273 times smaller.

This shortening of wavelength results in the emission due to passage from one orbit to another, being in the range of very soft X-rays, of very low penetrating power, instead of being in the spectrum of visible light. In consequence, it is difficult to identify them and study them.

The heavier mesonic atom should emit shorter waves, i.e. harder X-rays of greater penetrating power.

How far do these assumptions agree with the results of experiments?

To produce mesonic atoms, a particle accelerator is needed of a power rating sufficient to produce fluxes of negatively charged mesons by bombarding substances, plus a device in which these mesons are slowed down to thermal velocities and then captured by the atomic nuclei of appropriate elements, and lastly counters enabling the wavelengths of X-rays emitted by the excited mesonic atoms to be identified and measured.



How energy is absorbed and emitted by an ordinary atom and a mesonium

The first experiments were conducted with mu-mesons. When these were captured by relatively light atoms (e.g. neon or carbon) everything developed as anticipated; the wavelength of the X-rays emitted as the mu-mesons passed from one orbit to another agreed with the 210-fold difference between the masses of the mu-meson and electron. But with heavy atoms this ratio was abruptly disturbed; the energy of the X-rays dropped considerably, although the laws of radiation are valid for atoms of every kind.

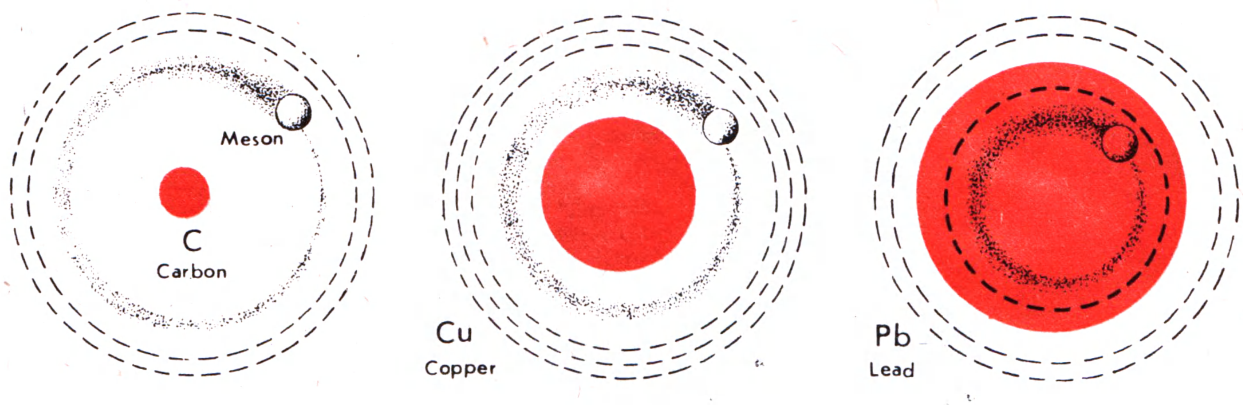
What happened to the mesonic atom then?

Analysis of the phenomenon showed that the theoretical calculations based on quantum theory were reliable and accurate. An answer to this question can be obtained by calculating the location of the mesonic orbits around the nucleus of a heavy atom like lead. If one of its outer electrons is replaced by a mu-meson, the diameter of the orbit accommodating the meson should be 5.8×10^{-13} cm. But the diameter of the nucleus of lead is 17×10^{-13} cm. So it turned out that the meson orbit was almost a third of the diameter of the nucleus of its atom: in other words, the meson would have to rotate inside the nucleus. Incredible, but a fact!

We know that the atomic nucleus is an exceptionally dense body. But density does not necessarily imply opacity. Opacity is a concept applicable only to our world, the macroworld. In the world of atoms, apparently, there are other concepts. And the possibility is not wholly excluded that a meson could travel freely inside a nucleus without interference.

And that is exactly what happened in our case. After completing a tremendous number of revolutions, millions of millions of them, in a short time (a hundred millionth of a second or ten nanoseconds) the meson was then absorbed by the lead nucleus, and the energy equivalent to its mass burst the nucleus with great force. The energy released was quite considerable.

Having measured the wavelength of the X-rays emitted by a mesonic atom, scientists then employed the results to calculate the diameter of the nucleus. In accordance with current views on the subject, an atomic nucleus is thought of as a cloud of electric charge, very dense, but ideally 'fluid', owing to which it offers no resistance to the movement



What happens to the mesonic atom of elements like copper and lead that are heavier than carbon. In an atom of lead the orbit of the meson passes inside the atomic nucleus

of a meson. The results obtained with pi-mesons are also of great interest.

Unlike the mu-meson, the pi-meson reacts with the atomic nucleus much faster and more strongly. In a mu-mesonic atom of hydrogen the mu-meson is free to orbit around the proton for the comparatively long time (on atomic scale) of several microseconds. Then, it disintegrates into an electron and several neutrinos.

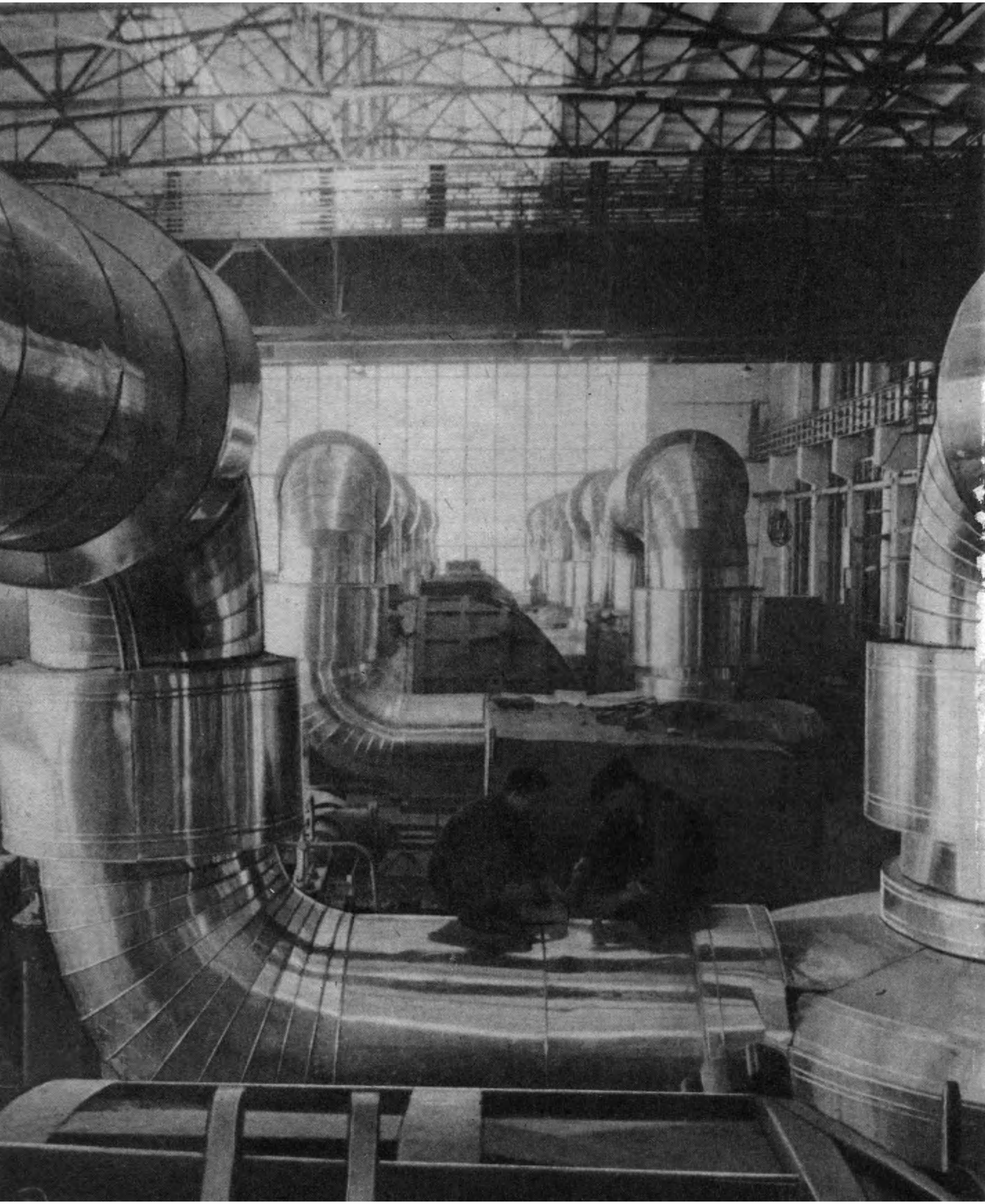
When the meson component of such an atom is a pi-meson things are quite different. As soon as it comes into the orbit closest to the nucleus, it jumps out of it and is captured by the proton, with the result that the life of a pi-meson in a mesonic atom is a million times shorter than that of a mu-meson. The negative pi-meson then combines with the positive proton, their charges neutralize each other and they turn into neutral particles.

In a heavier atom this phenomenon develops in an even more picturesque way. In a neon atom for example, the pi-meson never reaches the orbit closest to the nucleus; it is absorbed as soon as it reaches the orbit next to the last.

The 'greediness' of the atomic nucleus for pi-mesons is quite incredible. And in heavy atoms like lead, for instance, inside whose nucleus the pi-meson is free to rotate almost unhindered, the particle is captured by the nucleus from the fifth or sixth orbit away. This has been confirmed experimentally by the fact that there is no X-radiation associated with closer orbits.

After a pi-meson has been captured by the nucleus, it vanishes completely. And as with mu-meson capture, the energy equivalent to its mass breaks the nucleus up into a host of fragments. On a stack of stripped photographic emulsions it shows up as a clearly expressed star.

The picture of the mesonic atom that we have painted, and of its orbits, etc., is very simplified; the particles that we have made to travel in orbits are actually 'smeared' over the entire volume of the atom, and are constantly in contact with the nucleus in some manner.



Chapter Seventeen

CAN THE HYDROGEN BOMB BE TAMED?

What About Making Small Change?

We have already seen that the controlled chain reaction, like that in a nuclear reactor, is the explosion of an atomic bomb slowed down millions and millions of times.

But what is to be done with the hydrogen bomb?

There is no doubt that a gigantic thermonuclear explosion is a sublime and captivating spectacle. But it is hardly likely that there will be many chances when so tremendous an amount of instantaneously released energy can be effectively used on Earth. It is therefore desirable to slow the fusion reaction down and make it manageable.

One can spend hours admiring the formidable beauty of the Victoria Falls, or Niagara, or the Kivach Falls, or the turbulent rapids of the wild Angara River. But, having admired the beauties of nature to its heart's content, the human mind begins to calculate the power resources in the water, and to look for ways and means of converting these thousands of millions of wasted kilowatt-hours into electricity without spoiling the natural beauty of waterfalls and rivers.

So far man has only learned how to materialize the nuclear energy released by the fusion of the nuclei of light elements into nuclei of helium by exploding an atomic bomb inside a device known as a hydrogen bomb, filled with substances containing isotopes of hydrogen and of other light elements. Much more energy is released that way than by the explosion of an atomic bomb, but it is liberated all at once.

Having created the hydrogen bomb, honest-minded scientists could not help pondering, of course, over the complicated problem of how to control this new energy, the wildest and most restive horse of the Twentieth century.

It is impossible that, having discovered a new physical phenomenon, man should not learn how to control it! Since it is possible to lock nuclear energy up safely and securely in a reactor and tame it, man can find a way to lock up the terrifying wild beast of this new thermonuclear energy, and tame it.

What, in fact, prevents him doing so?

The thermonuclear reaction of the form we knew so far can only take place when a mixture of isotopes of hydrogen is heated to a temperature of hundreds of millions of degrees and subjected to a pressure of the order of thousands of millions of atmospheres. Such conditions, which apparently exist continuously inside the Sun and stars, can be created on Earth only for two or three millionths of a second inside the shell in which an atomic bomb is exploded. And man still cannot create such pressures and temperatures for any longer a period.

Can anything be done about it?

Let us assume for the moment that scientists will succeed in time in creating devices that would permit the explosive force of the hydrogen bomb to be reduced 100 times, say, or 1 000 times. That would still be insufficient, which means that the nuclear energy released by the fusion of hydrogen is doomed for a long time, so long as it remains bound to the atomic bomb, to be a 'giant' capable of splitting a whole mountain range or destroying an island in the ocean, or creating a new one, but not able of moving a spaceship even one millimetre without destroying it, or of lighting the bulb of a pocket electric torch.

Theoretically, however, if we could create the pressure and temperature developed by the explosion of a large atomic bomb if for just one millionth of a second in one cubic millimetre of hydrogen atoms, a thermonuclear fusion reaction would take place and a comparatively large amount of energy released from that small volume.

Continuing this reasoning suppose we could do it with 1/10, 1/100, or 1/1 000 of a cubic millimetre, that is, practically any small volume, thereby bringing the amount of energy released in the thermonuclear reaction to the desired magnitude. Suppose we could break it up into 'small change'? All we would need would be to create the required temperatures (hundreds of millions of degrees) and pressures.

Are there ways of creating them?

At present there are none. But it is safe to say that sometime in the future, and perhaps in the not so distant future, it will be done.

What grounds have we for such certainty?

The 'Scream' of Colliding Galaxies

Astronomers and astrophysicists have long been interested in the origin of the filamentary nebulae, which consist of very long but relatively narrow bands resembling a veil, one of which can be easily seen in the constellation Cygnus. Only recently have scientists succeeded in showing that these luminescent bands are the result of the propagation of special shock waves in a mass of intergalactic gas (presumed to be very rarefied hydrogen). Propagating at enormous velocity, these waves cause the gas to glow, i.e. to emit waves of visible light and very intense radio waves.

The glowing bands observed in the Cygnus are perhaps the result of a colossal, never surpassed cosmic phenomenon, the collision of two gigantic galaxies. The collision of two gaseous nebulae belonging to these galaxies caused the appearance of shock waves in the gas, whose temperature and pressure apparently greatly exceed those developed in the explosion of a hydrogen bomb.

Could the conditions of that grandiose cosmic phenomenon be transferred to our tiny Earth? Not, of course, completely, that is impossible; but partly, yes. For the conditions created in the explosion of an atomic or hydrogen bomb exist only in the depths of the Sun and stars.

In recent years scientists have succeeded in creating shock waves in gases in terrestrial conditions resulting in the development of temperatures that are still 'low', around several million degrees.

Such temperatures at present can only interest astronomers and space engineers. But this temperature range covers very important physical processes that may undoubtedly interest physicists in the near future.

We refer to the tubular chamber in which shock (or blast) waves can be created in a gas, developing tremendous pressures for a short period of time. Its operating principle is based on the well known fact that a gas heats with rapid compression. When this pressure increases at enormous speed, as with the shock wave created by an explosion or the flight of a supersonic aircraft, much of the energy is turned into heat by the motion of the gas. At speeds four times that of sound (Mach 4), the leading section of a jet aircraft would be heated to nearly 1 000°C, if it were not cooled intensively. At a speed ten times that of sound (Mach 10) the shock wave can heat gas to a temperature above 3 000°C, and at Mach 20 to 6 000°C. And finally, at Mach 620 temperature rises to a million degrees.

The chamber is a tube divided into two sections by a thin copper diaphragm. In one part a mixture of hydrogen and oxygen is burned, creating high pressure that rises until the diaphragm breaks. A shock wave is then formed in the gas in the second part of the tube with a velocity that may be 20 or more times that of sound.

In another type of tube gas is exploded by a powerful electric discharge, which gives a shock wave with a velocity 34 times that of sound.

Evidence of the deep changes that the atoms of the gas undergo is by the dazzling bright glow at the spots where maximum compression of the gas in the shock wave takes place. By passing a beam of this light to a spectroscope, the temperature and pressure of the gas can be determined.

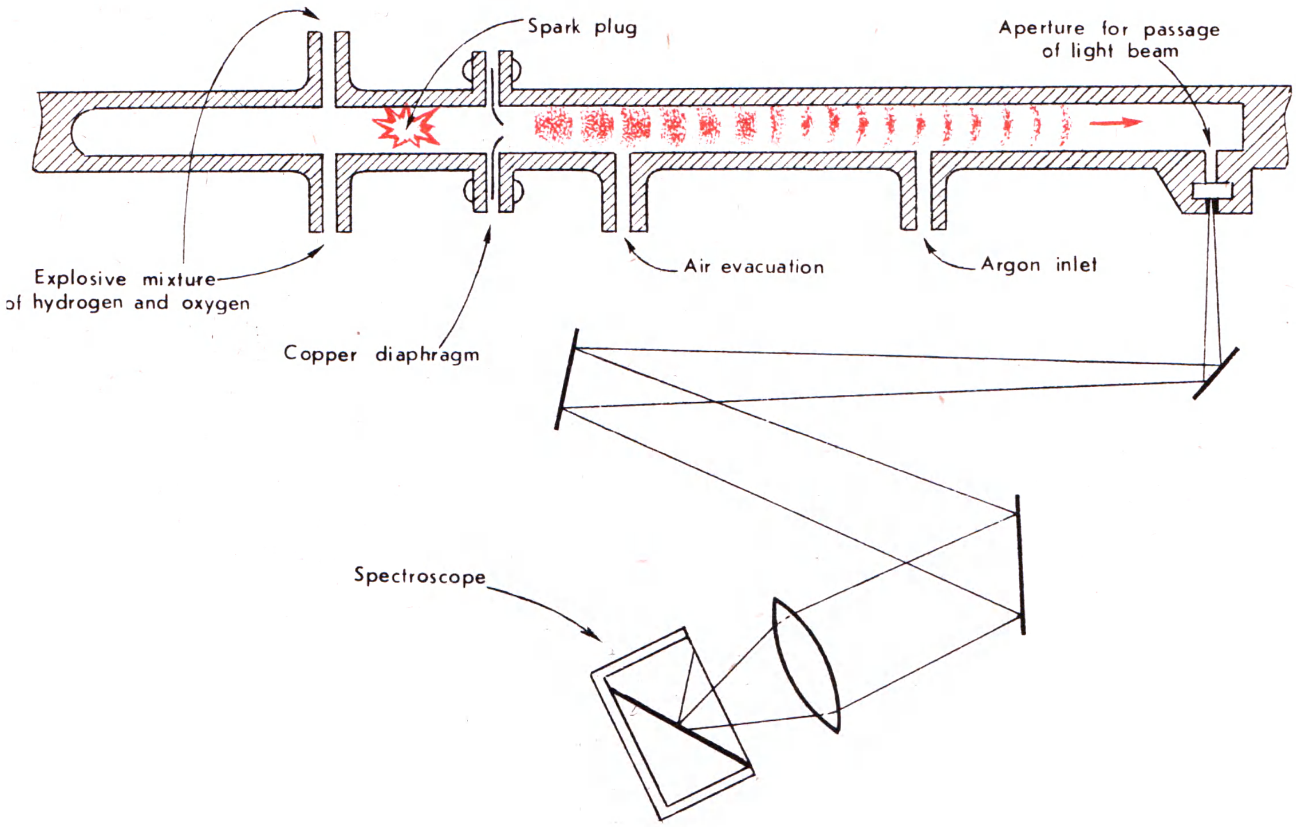
Let us imagine that we have the technical means to create powerful instantaneous shock waves in hydrogen gas, the temperature and pressure of which is close to those obtainable by the explosion of an atomic bomb. In principle there are no special obstacles to that. The small number of atoms of hydrogen isotopes confined in the working chamber of such an installation would be able to unite or fuse into helium atoms, releasing enormous energy.

Plasma, the Fourth State of Matter

Our everyday experience, limited to the surface of a comparatively dense and not too hot planet and its immediate surroundings, has led to the belief that matter can exist only in three states: viz. solid, liquid, and gaseous. These three states are most clearly illustrated by water, which occurs as ice, liquid, or steam.

But when we consider the Universe as a whole, or even just our Galaxy, the picture is quite different. The amount of matter encountered in these three states is infinitesimal, what chemists call 'traces'.

Matter simply cannot exist in the solid, liquid, or gaseous state, either in the inconceivably hot stars, or in the



Tubular chamber used to generate shock waves

clouds of the glowing hydrogen that fill the larger part of space, and they constitute almost the whole 100 per cent of matter in the Universe.

We have already said that stationary matter does not exist and cannot exist in nature. Every random movement of molecules, atoms, and atomic and nuclear particles is lined with temperature. The higher the temperature of a body or substance, the faster and more intensive is its motion, and, consequently, the frequency of collisions.

And the more intensive and frequent the collisions, the sooner are the bonds weakened or broken that hold together the molecules of a substance, the atoms of molecules, the atomic particles of atoms and the nucleons of atomic nuclei.

The first to break is the crystal lattice of a solid, which generally, except in certain organic substances, first softens, then melts and turns into liquid. The most refractory or infusible solids are converted into liquids at temperatures below 3 000-4 000°C.

Water can remain in its liquid state only to a temperature of 100°C. Above that it turns into steam, but it can be kept in the liquid state by tremendous pressure. At temperatures above 2 000°C, no pressure, however large, can prevent water from turning into steam, so no aqueous reactions exist in nature above that temperature.

At temperatures above 4 000°-5 000°C the last intermolecular bonds break, and substances decompose into their constituent atoms; and this means that all usual chemical reactions cease.

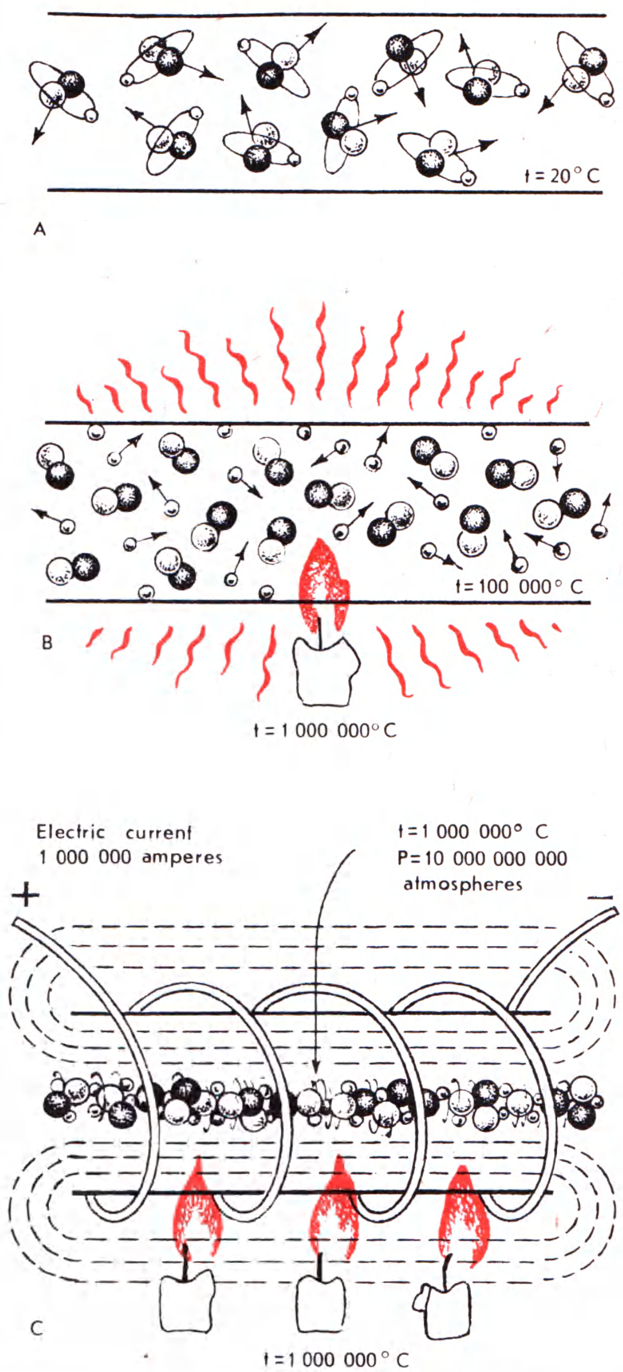
Only gas remains, but a rather unusual

gas. To grasp what it is like, let us consider the behaviour of any pure gas when heated.

As the temperature rises the motion of the molecules of the gas becomes more and more energetic and they collide with each other with ever increasing force. Then the electrons of the outmost shells, which are most weakly bound to the nuclei of their atoms, begin to be detached, and a kind of a second gas consisting of free electrons appears in the gas. After them electrons 'sitting' in deeper shells, closer to the nucleus are affected. This process leads to dissociation of the molecules of the gas, i.e. decomposition of the molecules into ionized atoms.

The frequency of collisions between ionized molecules and atoms that have lost all or part of their electrons increases and intensifies. And the gas, the molecules of which have been separated by the effect of very high temperature into free electrons, stripped nuclei or ions, and atoms that by sheer luck still retain a few electrons, all rushing helter-skelter about at breakneck speed and continuously colliding with one another and the confining walls of the vessel, has been called 'plasma' by scientists because of its resemblance to the liquid of blood in which the corpuscles float.

Most of the matter of the Universe exists in this plasma state, stars, interstellar gas, and the insides of the planets. The 'ideal' plasma, in which all the atomic particles are completely separated, corresponds to a temperature of ten million degrees.



What happens when gas is heated to superhigh temperatures. *A*—at room temperature the atoms of gaseous deuterium in a discharge tube move in the most varied directions. *B*—when gaseous deuterium is heated to a temperature of 100 000°C; its atoms turn into plasma, i.e. they lose their electron shells; the nuclei and electrons, moving with tremendous velocity, bombard continuously the walls of the tube, transferring heat to them. *C*—an external magnetic field is applied to the tube; the rectilinear motion of the particles is turned into spiral motion, and the plasma is pinched into a thin column and isolated from the walls of the tube; as a result its temperature rapidly rises to a million degrees, and pressure—to ten thousand million atmospheres

But plasma is not simply a gas heated to an incredibly high temperature. It is an entirely different physical state of matter, with a whole number of important and quite unusual properties, that is to say, it is the fourth physical state of matter.

A plasma state can arise at lower temperatures, even at relatively low ones, for instance, if a gas is very rarefied. Before colliding, the particles of a rarefied gas have time to acquire velocities and collision energies corresponding to very high temperatures, though, because of the small number of colliding particles, the gas itself is at a relatively low temperature. Thus a vast but quiet crowd in a city square can be more or less inactive, whereas a comparatively small crowd of very excited people all rushing about can make a great commotion.

The flame of a candle, an electric arc, fiery jet stream escaping from the nozzle of a jet engine or rocket, are all plasma.

Also considered as plasma are a corona discharge, the Northern Lights, the glow of a luminescent lamp, St. Elmo's fire, the blinding flash of lightning, and many other phenomena.

Certain of its properties make plasma quite like gas. It is rarefied and fluid, but at the level of molecules and atoms, its structure is quite different, and it is this that accounts for the vast diversity of properties that sharply distinguish it from the other physical states of matter.

Gases are a quiet mixture of comparatively slow-moving molecules that behave in an almost independent way. They attract each other very weakly and repel each other much more strongly and when they collide, they rebound like billiard balls.

In plasma the atoms are ionized, i.e. they consist wholly or partly of charged particles that either repel or attract each other, and at the same time rush about with terrific velocity. Their kinetic energy makes plasma considerably hotter than any chemical flame.

Furthermore, plasma can have at least three different temperatures at the same time: (1) the temperature of fast electrons, which is the highest; (2) the temperature of neutral, non-ionized atoms, which is the lowest; and (3) an intermediate temperature corresponding to the motion of variously ionized atoms.

On the whole, plasma is electrically neutral, even when heated to very high temperatures, since it contains equal numbers of negatively and positively charged particles (electrons and ions). But if an external electric potential or field is applied to it, two kinds of electric conductivity develop: (a) negative (due to electron motion in one direction), and (b) positive (due to ion motion in the opposite direction).

At the same time plasma can flow like a liquid, and can react with other substances like a chemical solution. It is readily affected by external electric and magnetic fields. In certain conditions it is an excellent conductor of electricity, not a whit inferior to copper or aluminium.

Plasma can be cold, supercold, superhot, superfast, and superdense. But all these terms are arbitrary.

When applied to plasma, the 'cold' has a rather unusual meaning; it refers to a plasma heated to a temperature not exceeding a million degrees Celcius. At a temperature of 100 000°C plasma is considered 'supercold', and is of no interest, whatsoever for the time being, to nuclear physics. At temperatures above 100 million degrees plasma is considered 'hot', and it is classed as 'superhot' at temperatures above 5 000 million degrees. Superhot plasma is also termed 'relativistic', for its constituent

particles move at velocities almost equal to that of light.

Plasma can be compared to a system of monetary units used in nature to conduct most of the transformations connected with the production, conservation, and release of energy.

Stars are gigantic clusters of plasma or plasmoids, and the thermonuclear reactions developing inside them, and resulting in the release of incredibly vast amounts of energy, cannot take place in any other state of matter than that of plasma.

The Miraculous Spark

Electric charges have always attracted the attention of scientists. The possibility of charging a body to an enormous electrical potential, and then discharging it in an infinitely short time, through a thin conductor or a small volume of some substance, prompted the idea that a very large quantity of energy must be instantaneously released on the path of a blinding spark and, that, consequently, a very high temperature must develop at a correspondingly high pressure.

These considerations are illustrated by lightning, whose destructive force is well known. That is why, since the seventeen century, scientists all over the world, beginning with Franklin and Lomonosov, have intensively investigated this well known, but still in many of its details mysterious, phenomenon.

In investigating lightning, special attention is always given to the fact that the quantity of energy involved in this formidable natural phenomenon is tiny compared with the enormous force of the electric discharge. It has been calculated that the value of one lightning flash of medium intensity, expressed in turns of the price charged for electricity, is about 14 kopecks (or $12^1/_2$ US cents); in other words its energy is around three or four kilowatt-hours.

To pass across a layer of air several kilometres thick the natural capacitor formed by the storm cloud and the earth's surface (or by two clouds) needs be charged to a voltage of hundreds of millions of volts or more. And all the damage that lightning can do, is done by an electric current reaching a strength of tens of thousands of amperes.

Hence, with such high voltages and enormous currents three or four kilowatt-hours can only be released provided that the whole process develops in a very short interval of time, in less than thousandth of a second; and the destructive force of the explosion of a shell or bomb is determined by the fact that the explosion lasts an infinitesimally short time.

The electric discharge of artificial lightning installations, made by man, though thousands of times weaker than real lightning, will destroy any dielectric that exists and evaporate the most refractory metal in the twinkling of an eye, and make any body shine with a blinding glare.

Calculations and indirect measurements indicate that, at the moment of discharge, the temperature inside a spark can in favourable conditions reach millions of degrees.

And for that reason, interest in sparks, electric discharges in matter, immediately took on a very great, one may say fundamental, importance after discovery of the explosive thermonuclear reaction.

We have already said that this reaction can be harnessed only if ways and means are found to make it non-explosive. Solution of this problem, according to a most eminent Soviet physicist, the late I. V. Kurchatov, 'would relieve mankind of constant anxiety about the reserves of energy needed for existence on Earth'.

Since thermonuclear reactions can only occur when the temperature of matter rises to the point where, in the course of nuclear collisions due to thermal motion, it becomes possible to overcome all the strong electric forces of repulsion acting between atomic nuclei, the electric discharge (in gaseous deuterium, for example) which holds out hopes of obtaining momentary, superhigh temperatures, offers a most promising approach in the search for ways to control the reaction.

A discharge in a mixture of deuterium and tritium would present even greater possibilities, since an appreciable effect could be obtained at a lower temperature than with any other substance known. But in this case, too, in order to approach even the threshold of the thermonuclear reaction, it is a question of temperatures of the order of tens of millions of degrees and pressures measured in hundreds of thousand million atmospheres. At such temperatures all electron shells are stripped off the atomic nucleus, and the substance, deuterium or a mixture of deuterium and tritium, can exist only as plasma, a state or medium in which stripped atomic nuclei float, as it were, in a gas consisting of separate electrons.

But however fast the processes in which the nuclei of deuterium and tritium, uniting, form nuclei of a new substance, helium, releasing, in turn, an even greater quantity of energy, these processes nevertheless take a strictly determined time, during which the temperature and pressure of the plasma must be maintained at the level of the astronomic figures, already mentioned, millions of degrees and thousands of millions of atmospheres.

And that is a very hard nut to crack. With such temperatures nuclei and electrons, moving at enormous velocities, continuously bombard the walls of the vessel confining the plasma, transferring to them all the heat being formed in it.

But the most refractory material on Earth will not withstand a temperature above 4 000°C.

The difference is vast, and the position would seem hopeless.

But even if we had such a material and tried to heat plasma to this temperature, we would fail just the same. For at a temperature of several tens of thousands of degrees the quantity of heat lost by any vessel to its surroundings would become so great that it would tend to exceed the temperature of the plasma. And if the vessel was not insulated, no further increase in temperature would be possible inside it.

Let us consider an example. Let us say we begin to heat a large piece of metal on a primus-stove. Could we melt it all in a few days, or weeks, or months of continuous heating?

At first the temperature of the ingot would rise quite rapidly. But after a certain time it would cease to rise, no matter how long we continued to heat it. A state of temperature equilibrium would set in, at which the ingot, heated to a definite temperature, would lose (emit) as much heat to the environment as it received from the stove. Its temperature could then only be raised by raising the temperature of the burner; and then a new state of temperature equilibrium would set in.

Yet, theoretically, the ingot can be melted. All that is needed is to put it in an ideal vessel that would not lose heat to the surroundings. But, of course, such ideal heat insulators do not exist.

To return to our plasma, the pressure of the deuterium would rise with its temperature; and even at 100 000°C the pressure would amount to over one million atmospheres. A pressure of that magnitude could only be maintained

for a twinkling of second for otherwise the vessel would shatter instantly.

To solve all these very tricky problems, fundamentally new discoveries, methods, and inventions are required. The best would be some way of enabling a thermonuclear reaction to be started during which the particles of the deuterium having acquired tremendous velocities from the fabulous temperatures of an electric discharge, would not fly apart or carry thermal energy to the walls of the vessel, i.e. during which some kind of empty space, and consequently ideal heat insulation, would be formed between the vessel and plasma.

The motion of the particles would then be concentrated solely in the plasma itself, with the result that its temperature could rise to any magnitude, and the walls of the vessel would remain, figuratively speaking, 'cold'. At the same time the walls of the vessel would also be relieved of the monstrous pressure developing in the plasma.

But where are we to get a superstrong 'hand' that would hold and tame the particles rushing madly about inside the vessel?

The Energy of a Waterfall in a Glass Tube

In 1950 Soviet scientists, the then young physicist A. D. Sakharov and Igor Tamm of an older generation, suggested such a 'hand'.

This titan's hand, capable of accomplishing the seemingly impossible, i.e. erecting an invisible barrier between the plasma and the walls of the vessel, of taming the plasma and creating heat insulation, proved to be a powerful magnetic field.

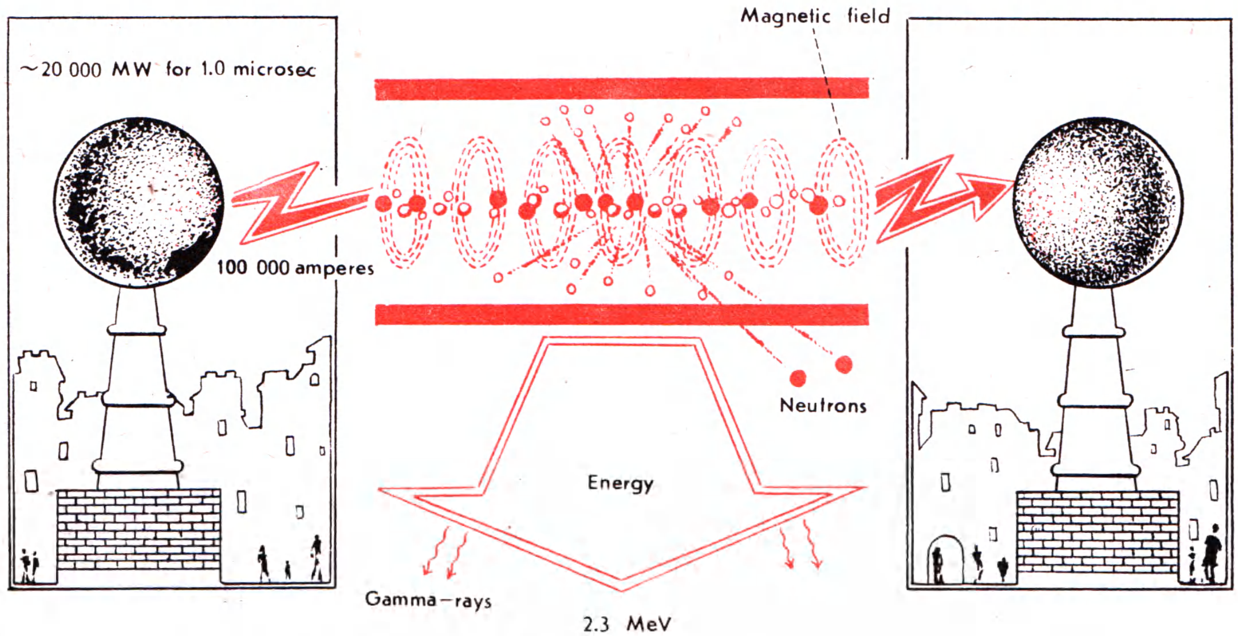
A magnetic field kills two birds at once. It radically changes the character of the motion of the heated charged particles (electrons and protons) in the plasma. Instead of rushing about, as a result of successive collisions, in straight trajectories, the particles begin to move in spirals the radius of which is the smaller, the stronger the magnetic field affecting them. As a result all the plasma concentrates at the centre of the vessel (along the axis of the tube) becoming a thin column; its particles do not reach the walls of the tube, while the pressure and temperature inside it rise continuously. The plasma proves to be imprisoned, and its energy is no longer borne away by the particles into surrounding space.

And it is not even necessary to create this magnetic field from outside. It is formed by itself whenever current flows through a conductor. All that is needed is to have a strong current of hundreds of thousands of amperes, so that the discharge will be stronger than an ordinary stroke of lightning. Then, according to the theoretical calculations, one could expect the material filling the vessel, in which the electric discharge occurs, to turn into plasma for a millionth of a second, and be compressed into a thin plasma column or pinch, separated from the walls of the vessel. Its temperature would reach millions of degrees, and the pressure would rise to thousands of millions of atmospheres, and a thermonuclear reaction would take place between the nuclei of the deuterium or of the mixture of deuterium and tritium. That is, of course, in the ideal case.

For the experiments to be considered successful, it would be sufficient for even a few nuclei to enter a thermonuclear reaction.

When one deuterium nucleus and one tritium nucleus unite a helium nucleus is formed, one excess neutron is ejected, gamma-rays are emitted, and energy equal to 14.6 MeV is released:

$$\text{deuterium} + \text{tritium} = \text{helium} + \text{neutron} + \\ + \text{radiation}.$$



One way of controlling a thermonuclear reaction. An electric discharge of a tremendous instantaneous power is passed through a tube containing deuterium or a mixture of deuterium and tritium. Through the effect of the discharge, simultaneously creating a high temperature and a very strong magnetic field, the deuterium is heated to several million degrees. The glowing plasma formed by the deuterium is concentrated into a thin column. Because of the cosmic temperature and pressure, a thermonuclear fusion reaction is initiated in the plasma, with the release of a large quantity of energy

The signal of this significant event then would be the emission of neutrons and gamma-rays—even just the ejection of one neutron, or the emission of a single quantum of invisible light (gamma-rays).

To avoid tremendous pressures, the discharge must take place in an extremely rarefied mixture of deuterium and tritium with a pressure of only 0.1 mm of mercury.

Soviet scientists were the first to conduct a series of such tests. An electric current of high power was passed through hydrogen, deuterium, and other gases in various degrees of rarefaction. In some of the experiments the maximum current was as much as two million amperes, and the power released instantaneously in millionths of a second, more than ten times the power of any of the huge hydroelectric stations on the River Volga.

The experiments were very carefully set up with measuring and control instrumentation. For it was necessary not to miss identifying a single neutron. For on its identification depended not only the fate of the experiment, but also a new direction in science.

For this bold raid into the future, the whole arsenal of modern experimental physics was put at the disposal of the scientists concerned, apparatus recording events occurring in millionths of a second, identifying single neutrons and quanta of energy, high-speed still and cine cameras to film all the processes.

This tedious work gave encouraging results. A plasma pinch whose temperature reached millions of degrees was actually formed in the glass tube of rarefied gas. Previously such a temperature had only been obtainable through exploding atomic or hydrogen bombs.

But by far the main thing was that

neutrons escaped from the discharge at certain moments of the experiment and gamma-rays were identified.

Of course, many of these experiments remained unclear and in the end indecisive. The emission of neutrons was possible not due to a chain reaction, but to some other process occurring in the plasma. The phenomena developing in the plasma turned out to be much more complicated than had originally been assumed by scientists in their theoretical calculations.

A 'Personage' with a Thousand Whims

Plasma is an exceptionally unstable formation. Very often, for no apparent external reason, it begins to 'rebel' and splash out of its confining magnetic field, and on hitting the walls of the apparatus, cools down instantaneously and immediately 'dies'.

For example, plasma undergoes a number of rapid, swiftly alternating compressions and expansions during a discharge, as if it breathed. During these alternate compressions and expansions it first concentrates along the axis of the tube then spreads to its walls with tremendous velocities of 100 km/sec. And very high overvoltages develop instantaneously in it which may be to blame for the appearance of neutrons and X-rays.

It is possible that individual particles of the plasma, colliding with each other in infinite combinations of velocity, acquire such great energy by chance that in the end they are ejected to the walls of the vessel no matter how strong the magnetic field.

It is not excluded that in certain, once again chance, favourable conditions a great many charged particles, moving in one and same direction at a certain moment of time can create their own magnetic field, capable of squeezing the plasma through the general magnetic field isolating the plasma from the walls of the apparatus.

After the first, apparently decisive progress, scientists had to get down to prolonged patient and tedious study of all whims and peculiarities of plasma, which proved to be very many, each more insidious than the last.

When scientists in some laboratory succeed in creating a temperature of the order of tens, or even hundreds degrees, this temperature can only be sustained for thousandths of a second or less. When they manage to extend this time to a hundredth, or even a tenth, of a second, the required temperature does not develop.

But why is it so important to study every one of the habits of plasma without exception?

The point is that the controlled thermonuclear reaction in plasma does not develop in the same way as in a hydrogen bomb, by an explosion, lasting millionths of a second. The duration of particle 'fusion' depends on the 'thickness' or density of the plasma. There is a definite 'thickness' that can be maintained by a given magnetic field of given intensity. When the thickness of the plasma reaches this maximum, fusion time is about one second.

Hence, it is necessary to contrive some kind of thermal insulation, i.e. to maintain temperature of the plasma (which as we already know, is 200 million degrees) for at least one second or longer if possible. In addition, for practical purposes it is necessary that the concentration of particles in the plasma be sufficiently great, since the rate of energy release is proportional to the square of their concentration. The higher the concentration, the shorter is the time the plasma can be confined; this requirement, as you see, contradicts the preceding one.

Since the initial technique, based on a discharge in a gaseous mixture, did not give promising results, and as plasma can be obtained by other means, scientists are going thoroughly into these other ways and methods.

A Magnetic 'Cage' for the 'Firebird'

We have already said that when a moving charged particle enters a magnetic field it begins to twist or spiral and the stronger the magnetic field, the more it spirals. The magnetic field affects the particle in a rather unusual manner, neither attracting it nor repelling it. The particle is wound, as it were, around invisible 'magnetic lines of force', of still unknown composition and origin, which affect not the movement of the charged particle but the magnetic field induced by it. Or rather, they change the motion only of charged particles whose path is perpendicular to the lines of force.

In view of this peculiar behaviour of charged particles in a magnetic field, work on designing and building plasma confining apparatus has followed two main directions, i.e. open systems and closed systems.

Imagine a section of enormous tubing from which air has been thoroughly evacuated. Fitted onto the tube are coils, wound from thick wire, and when direct current is passed through them a strong magnetic field is induced inside the tube.

Now if a cluster of electrons, or positively charged deuterium ions, previously accelerated to high energy, is injected into the tube through an opening at its centre, the electrons or ions will at once begin to wind along the lines of force of this magnetic field, collide with each other, and become heated. If, in addition, the intensity of the magnetic field is increased, and made stronger, it will begin to squeeze or pinch the 'garlands' of charged particles wound around the magnetic lines of force. The number of particle collisions will increase and the temperature of the plasma will rise even more. The plasma column becomes suspended in space, as it were. fully separated from the walls of the tube, which become 'cold', and no longer unable to transfer heat to the outside. The plasma proves to be locked in.

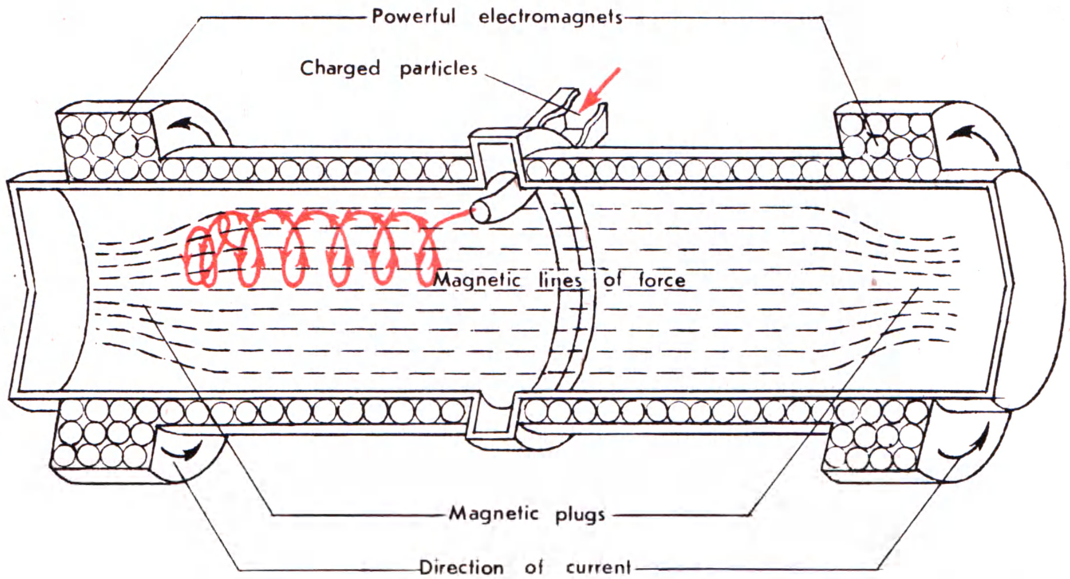
A spherical 'lump' of liquid, poured out of a vessel in the cabin of a spaceship, becomes suspended in rather the same way in the state of weightlessness, when the force of gravity ceases to act on it. Although not in contact with the walls of the vessel, the liquid preserves its spherical form solely because of the surface tension of its outer film.

Devices of this kind are known as adiabatic traps or in common parlance magnetic traps.

Our planet is an example of a magnetic trap. Charged particles striking it, instead of pouring down onto its surface in a death-dealing stream, begin to wind around its magnetic lines of force, forming the famous Van Allen radiation belts. Only comparatively few particles succeed in breaking through this peculiar magnetic shield and reaching Earth's surface. And fortunately for mankind a considerable part of these are trapped by the atmosphere, another, no less effective armour around our planet.

It may seem a bit embarrassing, but it turns out that we have squeezed our magic 'firebird' not into a cage but into a 'bottle'. The only consolation is that the 'bottle' is invisible and magnetic.

But, having pushed the scorching plasma away from the walls by means of a sufficiently strong magnetic field, we have, however, left it free to move



Schematic diagram of a magnetic trap ('bottle')

along the magnetic lines, from the 'lid' to the 'bottom' of the vessel. As it reaches them, it begins to lose heat intensively to the outside, so that it must also be pushed away from the ends of the vessel.

In order to 'pinch' the plasma in that direction scientists invented corks to 'plug' the bottle by intensifying the magnetic field on both sides of the central part of the trap. On being reflected from these corks, or rather 'mirrors', part of the plasma is thus blocked in a more restricted space and can be heated even higher.

In 1962, working with the rather more complicated BR-5 apparatus, fitted with longitudinal rods or 'sticks', Soviet scientists obtained plasma with good particle concentration at a temperature around 40 million degrees which it was possible to maintain for about 0.1 second—a very great success indeed.

But here, too, new kinds of plasma instability were discovered connected with the uneven distribution of particles in it.

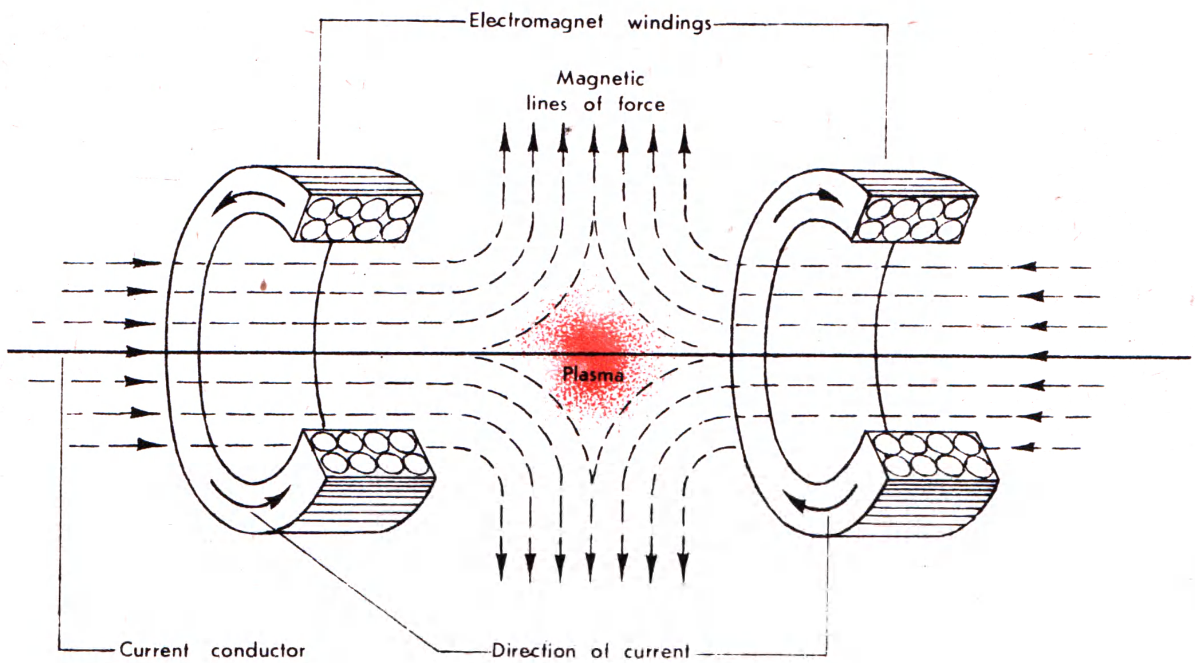
The other important direction of research concerns systems comprising closed plasma pinches, placed in a strong longitudinal stabilizing magnetic field. In these systems particles are forced to move along an endless (circular) tube affected by a longitudinal rather than a transverse magnetic field, with the plasma heated independently by passing strong direct current (a flux of electrons) through it.

To get rid of some of the drawbacks and whims of plasma this 'doughnut' has to be twisted into a figure of eight.

Improved magnetic fields and vacuums have enabled Soviet scientists, working with apparatus of this type, to produce temperatures of the order of two million degrees with a plasma concentration of the order of 2×10^{13} particles per cubic centimetre, and a life around 0.005 second.

Here, apart from the problem of heat insulation of the plasma, great attention had also to be paid to problems of heating it.

You already know that certain resonance phenomena, in cyclotrons for instance, enable charged particles to be accelerated. When plasma, trapped in a



One of the various kinds of magnetic trap

permanent magnetic field, is also affected by an alternating magnetic field, of a frequency close to the angular velocity of the spin of ions in the permanent field, the ions receive additional acceleration.

Ions have been heated to 10-12 million degrees by means of these 'ionic cyclotron waves' but, it is true, with a low temperature for the plasma electrons.

Of interest also are the efforts to employ the instability of beams of electrons when they interact with plasma in order to heat them further, for in all the numerous oscillations, twisting, overspill, and other 'twists' and 'turns' of the electron beam no little energy is used up.

Let us recall that plasma at any one time may contain particles of various kinetic energies and, consequently, different temperatures (like a mixture of three separate gases), for example, very 'hot' electrons, 'cold' ions, and 'quite cold' neutral atoms. Therefore, attempts are being made to employ plasma with 'hot' electrons, i.e. with electrons accelerated to high energies, in order to accumulate plasma containing 'hot' ions with their aid, or simultaneous combined heating of electrons and ions.

At the Novosibirsk Institute of Nuclear Physics the method known as impact heating is being worked on. When 'cold' plasma confined in a permanent magnetic field is also acted on by a short magnetic pulse, a strong impact wave can be induced in it, propagated across the permanent magnetic field. This technique has made it possible to obtain plasma with an ion energy around 10 000 electron-volts (10 keV).

But what would happen if cold, i.e neutral, ions were injected into the magnetic trap instead of hot ones? Not carrying charge, these ions would pass without hindrance through the magnetic 'walls'; but once they were inside the trap, they could be turned into plasma by means of a laser beam, and this plasma, caught up by the electro-

magnetic field, could be heated to the temperature required. But so far, of course, this is only a very tempting idea.

Improvement of the method of a self-pinching discharge of special shape (we began this section with a description of it) has recently made it possible to produce deuterium plasma heated to tens of millions of degrees, with a concentration of around 10^{20} particles per cubic centimetre in a volume of about one cubic millimetre for two or three tenths of a microsecond. During the experiment the appearance of some 10^{10} neutrons was recorded. When deuterium was replaced by a mixture of deuterium and tritium, the number of neutrons produced increased to $3\text{-}4 \times 10^{11}$. So far this is the only successful way of obtaining plasma with record parameters, close to those at which, it is calculated, thermonuclear reaction will begin (the neutron yield must be 10^{12} for a reaction in deuterium).

Will this phenomenon turn out to be the 'tomtit' promising to set the 'sea' to fire, a little brook running to an ocean of unlimited energy in the hands of man, or will the stream dry up, without hardly leaving its source? Only the future will show, but perhaps it is not far off. At any rate, it is worth recalling that as little as 0.2 gram of deuterium (heavy hydrogen), contained in a litre of ordinary water, could yield as much energy as 300 litres of petrol.

As often happens in science, the development of thermonuclear research has led to unforeseen 'side' effects. The development of plasma injectors for filling 'magnetic traps' has led to the creation of the plasma jet engines used in spaceships, and the research devoted to study of plasma jets in magnetic fields has given rise to a new trend, the development of plasma dynamos (or magnetohydrodynamic converters) for the direct conversion of heat into electricity (without steam boilers and rotating machines), of an efficiency of 50-70 per cent or higher, compared with the 35-38 per cent of the most efficient thermal power stations.

If Only ...

In Chapter XVI we spoke of the properties of atoms in which the easiest electron to remove, usually one in an outer orbit, is replaced by a 'weightier' mu- or pi-meson. The atom is squeezed at once to 1/210 or 1/273 of its diameter. It does not take great imagination to picture what our surroundings would be like, if alongside habitual things we used certain new things made of materials built up from mesonic atoms.

A nuclear reactor the size of a nut, surrounded with a shield one centimetre thick and cooled by a liquid 210 times thicker than heavy water or liquid metal. Armour-plate as thin as paper. A carpenter's hammer weighing around 250 kilograms. Indeed, it would be possible to 'pack' nearly three hundred atoms into a volume that previously scarcely accommodated one.

Alas!... all that is still only a theoretical curiosity, more remote than the dream of releasing intranuclear energy was a century ago. No one can yet imagine how the electrons of an atom could be replaced by mesons.

Above all, of course, mesonic atom would have to exist not for nanoseconds, but at least for one whole second, not to speak of hours or decades. But scientists have already begun to dream. And their dreams go much farther ahead than anything that man has dreamed about so far. New times, new dreams!

Here is one, perhaps the most fascinating one. A few years ago the Soviet scientists Zeldovich, Sakharov, and Markov concluded after lengthy calculations

and theorizing that a thermonuclear fusion reaction in which hydrogen was fused into helium could develop without the release of enormous quantities of heat, without inconceivable pressures and temperatures, and without the need to create a much too hot piece of the Sun on Earth. All that would be needed would be mu-mesonic atoms of hydrogen.

A mesonic atom, on encountering an atom of deuterium, would come so closely to it that the negative meson would begin to rotate around both the hydrogen atom and the deuteron, drawing them closer and closer together until a peculiar mesonic molecule was formed that would live for millionths or so of a second; then the two particles, coming into the sphere of action of intranuclear forces, would finally be drawn into a helium nucleus. That, as you know, should be accompanied by the release of 5.4 MeV of energy. The mu-meson having done this useful job would find itself 'one too many' in the helium nucleus, where there is no place for it. The colossal energy released during the formation of the helium nucleus would eject the mu-meson from the nucleus, and having expended a good part of its energy in collisions with other atoms, the mu-meson would become stuck in one of them, knocking out an electron and taking its place to form a new mesonic atom of hydrogen. Such a roaming, unchanged and eternally whole atom could create new mesonic atoms and molecules, and then a vast, ever multiplying generation of new helium nuclei.

Still more grand is the dream of a controlled nuclear fusion reaction.

But the life of a mu-meson is so short that it has only time at best to unite one or two pairs of hydrogen and deuterium nuclei into a helium nucleus, then, having generously expended its energy, it explodes in a millionth of a second, splitting up into an electron and two neutrinos.

As you can see, it hangs on a trifle — of finding ways of extending the life of a meson a million million million times (10^{18}). Or creating a source of mesons that would maintain the number of newly formed artificial atoms at the level needed to sustain the reaction, so that each time a meson that had accomplished its task died, a new one would immediately appear.

This reaction in which the meson would play the role of a nuclear catalyst, has been called catalytic.

It is still difficult to guess what kind of breathtaking discoveries scientists will make in the near future. Only one thing can be said with certain—the authors of science-fiction, describing the near and remote future, will procure energy for their spaceships from the cold fusion of long-lived mesonic atoms of hydrogen into nuclei of helium-3, or by forming anti-matter from anti-protons, anti-neutrons and positrons and uniting it with ordinary matter convert the two into light quanta that will propel a photon rocket into cosmic space at a speed close to the velocity of light.

Having curbed the monstrous hydrogen bomb, man will be able to change the thousands of millions of kilowatt-hours of its energy into smaller quantities to be utilized at will. Compared with the unlimited possibilities that will be placed in the hands of man, atomic energy will appear in the same light as the energy released by the explosion of dynamite seems today alongside the explosive force of an atomic bomb.